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March 1972

Y TO
ELTERBELT INSECTS
THE NORTHERN
EAT PLAINS

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Patrick C. Kennedy
Mountain Forest and Range Experiment Station
t Service U. S. Department of Agriculture

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ABSTRACT

An insect key designed to help identify 227 insect species. Th
text contains 136 figures and 8 color plates to aid in identi
fication. Several tables assist in coordinating host damage with
particular insect species.

Key words: shelterbelt insects, Great Plains forestry, windbreak

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KEY TO SHELTERBELT INSECTS IN THE NORTHERN GREAT PLAINS

by

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PREFACE

Trees and shrubs are planted throughout the Great Plains fo various reasons: crop and soil protection, livestock protection wildlife habitat, noise abatement, snow fences, beautification and privacy screens. These trees represent a considerable invest ment of both public and private funds to obtain the intende benefits.

Establishing shelterbelts on the prairie provides a favorabl habitat for tree pests which could not otherwise exist in th region. These potential pests must injure the tree to survive. I the injury results in a damaged tree, then the insect or mite mus be correctly identified for application of recommended contro measures.

This publication is designed as an aid in identification of insect for those who have no specialized training in entomology Numerous illustrations are included for ease of identification an to insure discrimination among similar insect species. Insects ar identified by proceeding through a series of alternative choice presented in brief paired statements (couplets). Included in th final couplets are principal hosts and time of insect occurrence. A glossary of terms used throughout the key is provided in th appendix. Also in the appendix is a list of the common an botanical names of the trees and shrubs mentioned.

The majority of insects defoliating trees in North and Sout Dakota are larvae of moths, butterflies, and sawflies. Sinc chewing of foliage is not distinctive, identifying characteristics c the insect rather than the damage are included in certain portion of the key. Characteristics given for immature forms are base upon last instar larvae unless otherwise stated.

The individual who encounters an insect or insect damage in shelterbelt should note: (1) the kind of injury and its appearanc (2) the tree species, and (3) the general appearance of the inse doing the damage. With this information he can be relatively sur of obtaining an identification. In the case of defoliation, it usually imperative that the insect causing the damage be we preserved for correct identification. Larvae stored in alcohol ma lose their color and may not be identified correctly in this ke Where damage is diagnostic, the insects have not been describe

To use the key, examine the insect or damage and place it int one of the four **Major Damage Categories.** Identification is the

made by going through a series of opposing alternatives, one of which should apply to the specimen. Each alternative gives either a number referring to the next pertinent couplet, or a name identifying the specimen. Couplets have a number in parentheses which refers back to the previously used couplet. Therefore, one is able to retrace his steps in the key if he makes a mistake.

Example: Assume that warty eruptions were found on a leaf blade of green ash. Each gall was enclosed and protruded from both the upper and lower leaf surfaces. The description fits the **Major Damage Category** of gall-making insects and mites. Therefore, we start with couplet 1 in section II of the key.

Couplet 1 gives a choice between deciduous trees and spruce trees. The damage occurred on a deciduous tree, which leads us to 2. A series of hosts is listed in couplet 2. The damage occurred on green ash, which directs us to 12. Couplet 12 presents a choice between buds and leaves or staminate flowers. The leaves are affected, therefore we continue to 13. Couplet 13 presents the alternative of midvein or leaf blade. The leaf blade is affected, which refers us to 15. Couplet 15 gives a choice between galls or tightly rolled leaves. The obvious choice is the gall. Therefore, the damage is caused by a beadtype gall mite *(Aceria chrondriphora).*

Information contained in the key was obtained from material collected in North Dakota and South Dakota. However, the key should be appropriate for portions of Montana, Wyoming, Nebraska, Minnesota, and Iowa.

MAJOR DAMAGE CATEGORIES

Defoliating Insects (Section I)

Insects feed directly on the leaves and needles of deciduous or evergreen trees and shrubs. Insects may roll, fold, or tie leaves or produce extensive webbing. This section includes adult and immature insects . . . . . .Page 1

Gall-Making Insects and Mites (Section II)

Galls appear as abnormal woody growths or swellings on twigs and branches, closed leaf galls, warty eruptions on leaf blades, rosette-type leaf clusters, or abnormal fruit. All aphids found in leaf curls are included with the sap-sucking insects (Section IV) . . . . . Page 54

Boring and Leaf-Mining Insects (Section III)

Insects feed internally on woody tissue, fruit, seeds, or leaves. Borers associated with abnormal swellings are included with the gall-making insects (Section II) . . . . . Page 83

Sap-Sucking Insects (Section IV)

Insects feeding on plant sap produce puncture wounds, stippled discoloration, or leaf curl; scale insects . . . . .Page 131

SECTION I. DEFOLIATING INSECTS

Insects feed directly on leaves and needles of deciduous or evergreen trees and shrubs. The insect may roll, fold, or tie leaves or produce extensive webbing.

1. Insect rolls, folds, or webs leaves 2
1'. Insect defoliates without webbing or leaf distortion .16

2(1). Leaves rolled or folded 3
2'. Leaves webbed together, or have a silken mat 8

3(2). Leaves folded 4
3'. Leaves rolled 6

4(3). Found on bur oak 5
4'. Found on cottonwood. Leaves folded toward ventral surface (fig.1), inner surface skeletonized. Larvae present during early summer. *Phyllocolpa bozemani* (Cooley) . . . . . **poplar leaffolding sawfly**

Figure 1.—Poplar leaffolding sawfly (*Phyllocolpa bozemani*) on cottonwood leaf.

5(4). Leaf margin folded (fig. 2). Larvae present during summer. *Itonida* sp. . . . . **a leaffolding fly**

5'. Leaf lobe folded (fig. 3). Larvae present during summer. *Cecidomyia* sp. . . . . **a leaffolding fly**

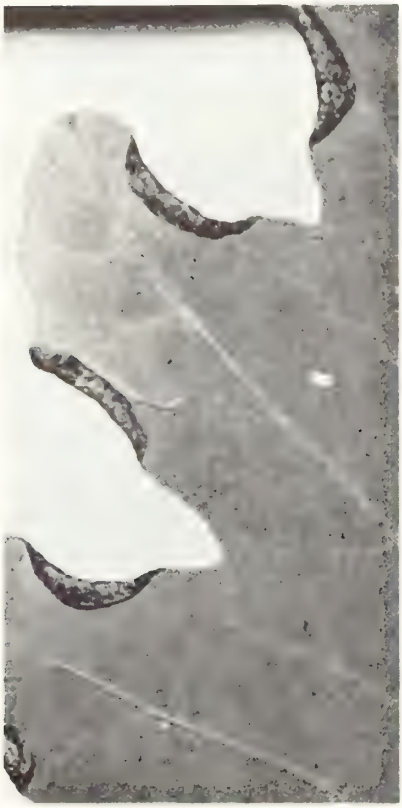


Figure 2.—*Itonida* sp. on bur oak.

Figure 3.—*Cecidomyia* sp. on bur oak.

6(3). Leaf roll without prominent silken frass tube . . . . . .

6'. Leaf roll with prominent silken frass tube (fig. 4). Bu oak. Larvae present from July to September. *Acrobas* sp. . . . . **a leafrolling mot**

Figure 4.—*Acrobasis* sp. on bur oak. Note silk tube with incorporated frass. Larva skeletonize inner surface of leaf roll.

7(6). Feeds on boxelder (fig. 5). Larvae present from June to August. *Gracillaria negundella* Chambers . . . . . **boxelder leafroller**

7'. Feeds on green ash. Head, thoracic legs (fig. 7) and cervical shield light brown to black; body light green to dusky gray (fig. 6). Larvae present from June to July. *Archips argyrospilus* (Walker) . . . . . **fruittree leafroller**

8(2). Larvae construct silken mats on ventral leaf surface . . 9

8'. Larvae web or tie leaves together 10

Figure 5.—Boxelder leafroller (*Gracillaria negundella*).

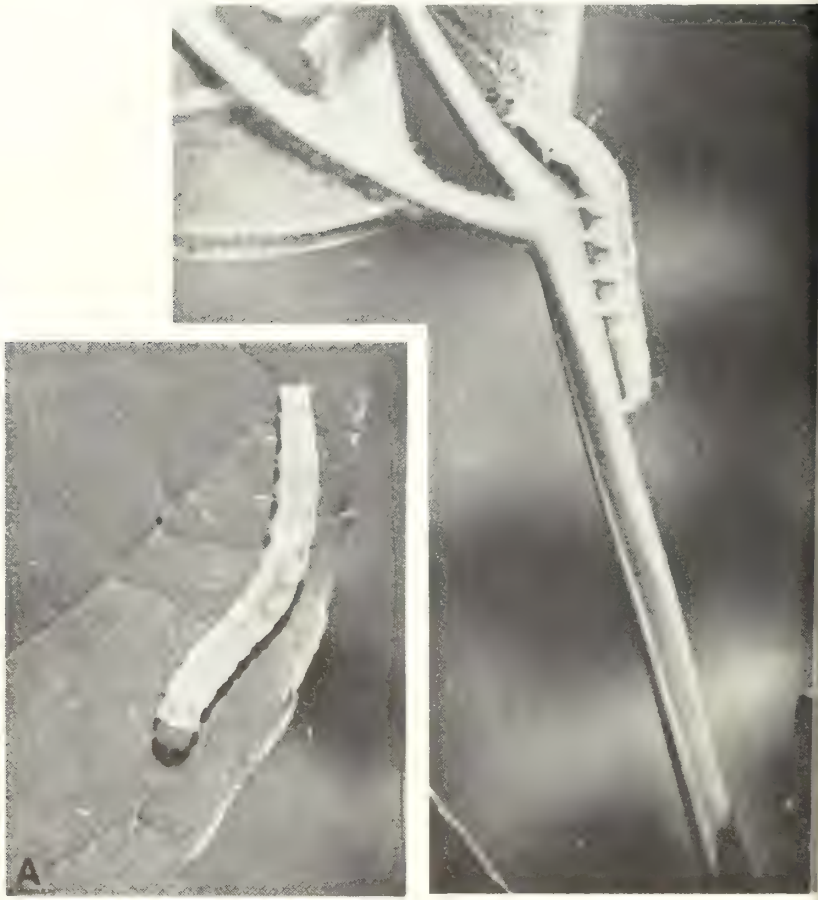


Figure 6.—Fruittree leafroller (*Archips argyrospilus*): A, dors
view of last instar male larva; B, lateral view ; C, p.

Figure 6C.—Dark phase larva inside leaf roll.

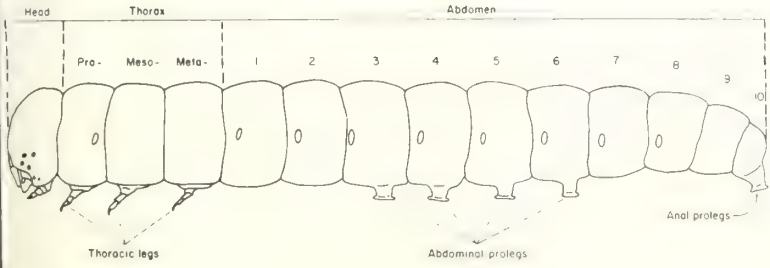


Figure 7.—Generalized drawing of a caterpillar.

9(8). Found on American elm. Larvae skeletonize lower leaf surface. Head and body light green to reddish brown flecked with white; prothorax, mesothorax, and 8th abdominal segment (fig. 7) with a black spot; prominent setae. Larvae present from June to August. *Psorosina hammondi* (Riley)
. . . . . **appleleaf skeletonizer**

9'. Found on boxelder (fig. 8). Larvae skeletonize lower leaf surface. Head dark brown with black eye spots; body pale yellow. First, second, and third instar larvae present on leaves from July to October. *Proteotera willingana* (Kearfott) . . . . . **boxelder twig borer**

Figure 8.—Boxelder leaf skeletonized by third instar larvae the boxelder twig borer (*Proteoteras willingana*).

10(8). Larvae construct large tents or webs; gregarious defoliator 11

10'. Larvae web 2 or 3 leaves together; solitary defoliator. Head and body light green, prothorax and mesothorax (fig. 7) with dark spot on the side. American elm. Larvae present from July to October, two generations per year. *Canarsia ulmiarrosorella* (Clemens) ..... **a leaftieing moth**

11(10). Tents in branch forks 12

11'. Tents not in branch forks 14

12(11). Head brown or black 13

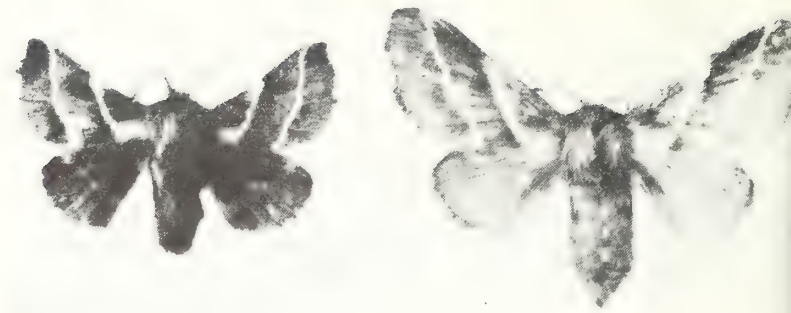
12'. Head blue mottled with black, body black with pale blue areas, interrupted white stripe down center of back (plate 6; fig. 9). Webbing contains frass and cast larval skins (fig. 9a). Common chokecherry, Siberian elm, Peking cotoneaster, rose. Larvae present from May to July. *Malacosoma californicum lutescens* (Neumoegen & Dyar) ..... **prairie tent caterpillar**

Figure 9.—Defoliation and webbing of the prairie tent caterpillar (*Malacosoma californicum lutescens*) on chokecherry.

13(12). Body pale yellow with a dark stripe down the back, head dark brown to black, setae long (plate 4; fig. 10). American plum, common chokecherry, willows, cottonwood, American elm, Siberian elm. Larvae present from July to October. *Hyphantria cunea* (Drury) . . . . . **fall webworm**

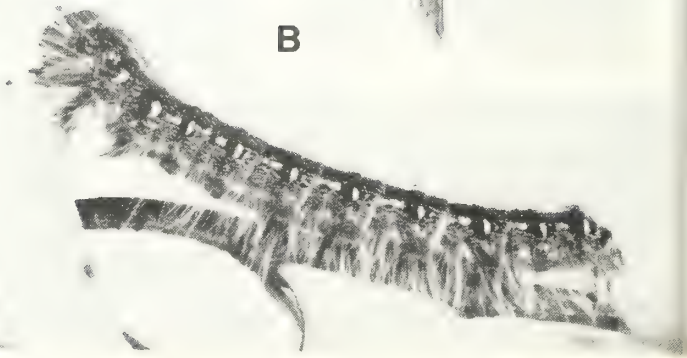
13'. Body black with pale blue areas, interrupted white stripe down center of the back, head black, setae long (fig. 11). Common chokecherry. Larvae present from May to June. *Malacosoma americanum* (F.) . . . . . **eastern tent caterpilla**

Figure 10.—Fall webworm (*Hyphantria cunea*): A, larvae and typical leaf skeletonizing; B, webbing in branch forks, characteristics of early instar larvae of both fall webworm and eastern tent caterpillar.



A

B



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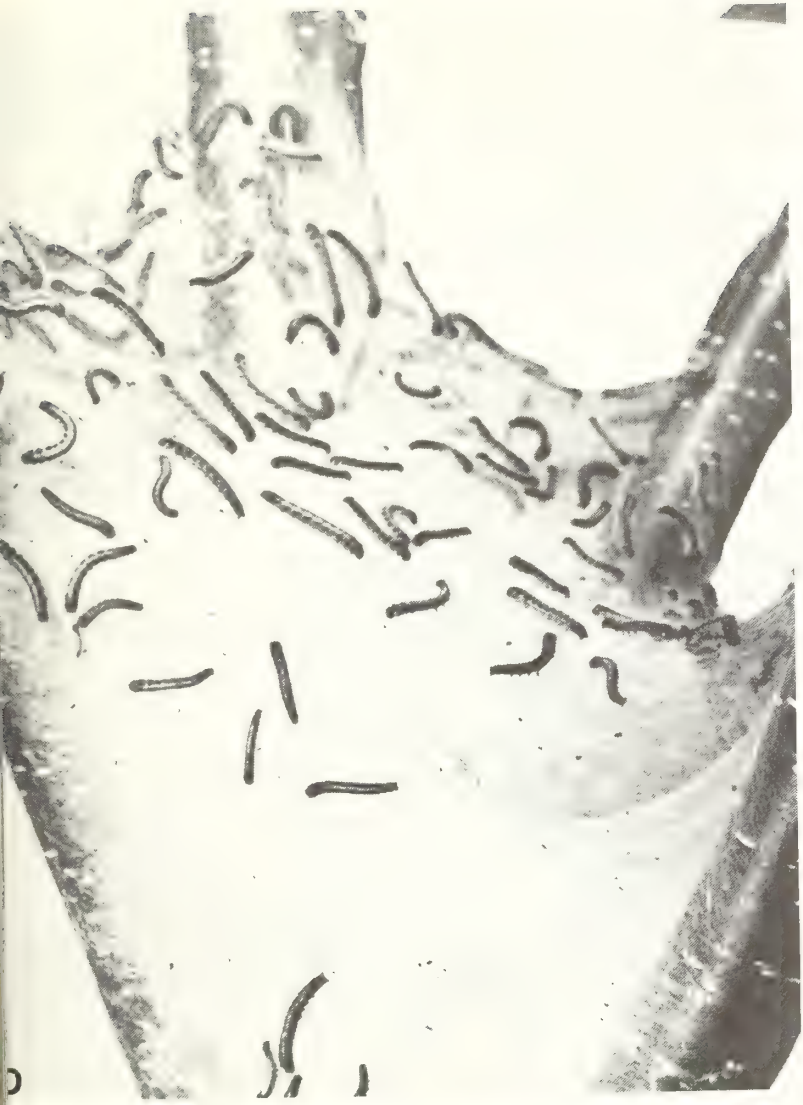


igure 11.—Eastern tent caterpillar (*Malacosoma americanum*): A, adults; B, egg mass; C, larva; D, larvae and webbing in branch fork.

14(11). Head blue or black 1
14'. Head light yellow, body white, thoracic legs and cerv
cal shield black, prolegs reduced. American plum,san
cherry. Larvae present during the summer. *Neurotom*
inconspicua (Norton) ..... **plum webspinning sawfl**

15(14). Head black, body yellowish white (fig. 12). Webbin
contains frass. Common chokecherry. Larvae preser
from May to September. *Archips cerasivoranus* (Fitch
..... **uglynest caterpill**
15'. Head blue mottled with black, body black with pa
blue areas, interrupted white stripe down center
back (plate 6; fig. 9). Webbing contains frass and ca
larval skins. Common chokecherry, Siberian eln
Peking cotoneaster, rose. Larvae present from May t
July. *Malacosoma californicum lutescens* (Neumoege
& Dyar) ..... **prairie tent caterpill**

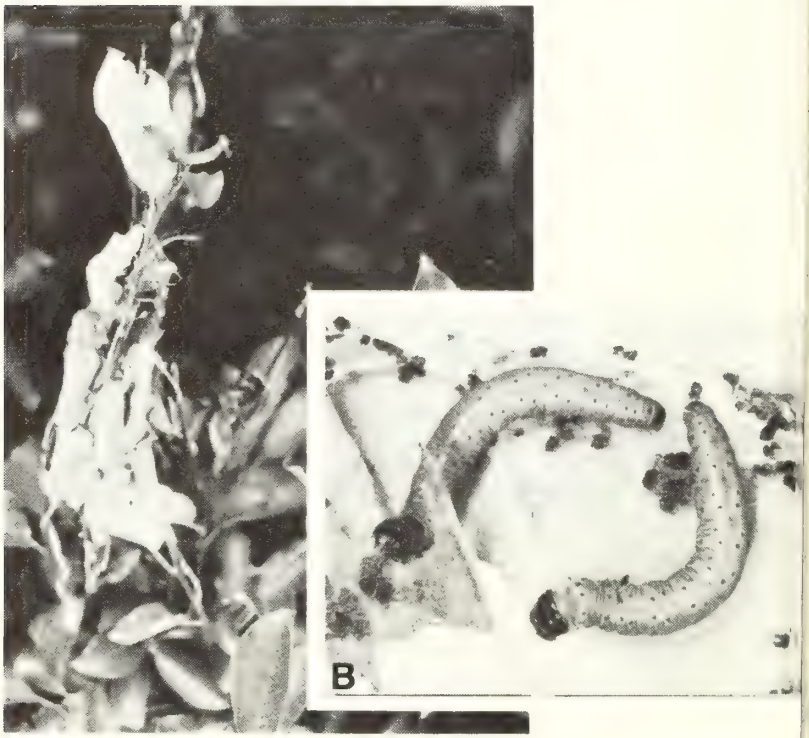


Figure 12.—Uglynest caterpillar (*Archips cerasivoranus*): webbed foliage; B, larvae.

6(1). Insect with wings or wing pads 17
6'. Insect without wings 32

(16). Front pair of wings (elytra) meeting in straight line down the back (fig. 13), leathery, veins absent. **Beetles** 18
7'. Front pair of wings not meeting in a straight line, leathery, veins present. **Grasshoppers** 30

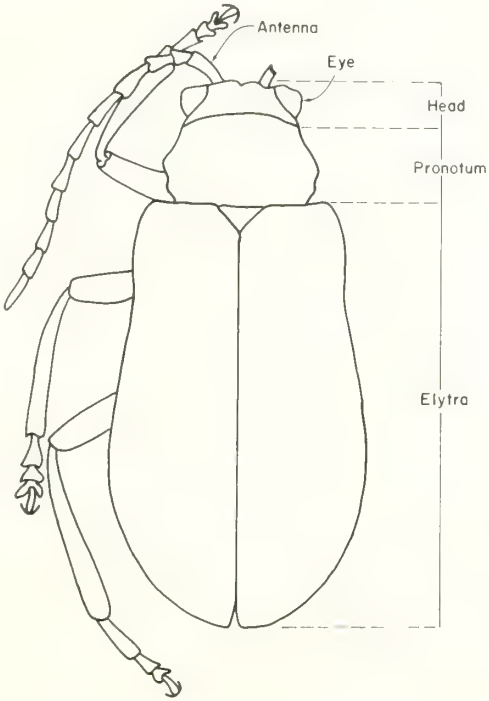


Figure 13.—Generalized drawing of a beetle.

(17). Mouthparts elongate and snoutlike (fig. 15a), antennae elbowed and club shaped (fig. 14a) 19
8'. Mouthparts not snoutlike, antennae filiform (fig. 17) or lamellate (fig. 10b) 20

Figure 14.—Types of antennae: A, elbowed and club shaped; B, lamellate.

19(18). Feeds on American elm., Siberian elm. Body
reddish brown, front wings with longitudinal li
coarsely punctate (fig. 15). Adults present from J
to August, shot hole type defoliation. *Maga*
armicollis (Say). . . . . **red elm bark we**

19'. Feeds on white willow. Body brown to black,
oblique band at end of forewing (fig. 16). Ad
present from July to August, feed on foliage and gc
notches in current season's growth. *Cryptorhync*
lapathi (L.) . . . . . **poplar-and-willow b**

igure 15.—Red elm bark weevil (*Magdalis armicollis*): A, adult, length 7 mm or less; B, adult and shot hole defoliation.

)(18). Lamellate antennae (fig. 14b), leaflike segments forming a club, antennae shorter than head and pronotum. **June beetles** 21

20'. Filiform antennae, longer than head and pronotum (fig. 13) 24

1(20). Body with metallic sheen 22

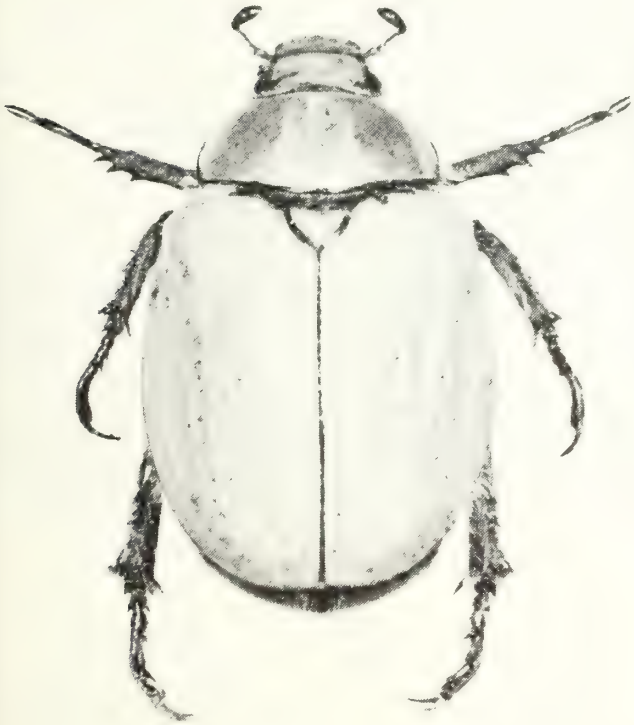
21'. Body without metallic sheen 23

Figure 16.—Poplar-and-willow borer (*Cryptorhynchus lapathi* length 7-10 mm; normal twig on the left and damaged twig on the right.

Figure 17.—*Dichelonyx subvittata* length 10 mm.

2(21). Head and pronotum (fig. 13) light brown, elytra brown with metallic green (fig. 17). Hardwoods. Adults present from July to August. *Dichelonyx subvittata* (LeConte) ..... **a June beetle**

22'. Head and pronotum metallic yellowish green, elytra lemon yellow to gold (fig. 18). White willow, cottonwood. Adults present from June to July. *Cotalpa lanigera* (L.) ..... **goldsmith beetle**



igure 18.—Goldsmith beetle (*Cotalpa lanigera*), length 20-25 mm.

Figure 19.—*Polyphylla hammondi*, length 26 mm.

23(21). Head and body dark brown, elytra (fig. 13) with indistinct gray longitudinal lines (fig. 19), medium to dark brown hair on underside of the body. White willow. Adults present during July. *Polyphylla hammondi* LeConte . . . . . **a June beetle**

23'. Head dark brown, pronotum and elytra (fig. 13) with yellowish-green tinge, elytra with white lines (fig. 20) light tan hair on underside of the body. White willow. Adults present during July. *Polyphylla decemlineata* (Say) . . . . . **tenlined June beetle**

gure 20.—Tenlined June beetle (*Polyphylla decemlineata*), length 27-30 mm.

(20). Pronotum narrower than the head and body. **Blister beetle** ..... .25

4'. Pronotum wider than the head (fig. 13). **Leaf beetle** ..... .27

(24). Body nonmetallic dark color ..... .26

5'. Body metallic purple with a green sheen. Siberian peashrub. Adults present from May to June. *Lytta nuttallii* Say ..... .**Nuttall blister beetle**

(25). Head and body ash gray (fig. 21). Siberian peashrub. Adults present from May to June. *Epicauta fabricii* (LeConte) ..... **ashgray blister beetle**

6'. Head and body black. Siberian peashrub. Adults present from May to June. *Epicauta subglabra* (Fall) ..... **caragana blister beetle**

Figure 21.—Ashgray blister beetle (*Epicauta fabricii*) on caragar
length 15-25 mm.

27(24). Body yellowish green to light brown, marked wi
spots or stripes .....
27'. Body metallic purplish blue, elytra smooth with
prominent ridge parallel to the outer margin. Comm
chokecherry, willow. *Altica plicipennis* (Mannerheim
..... **a chrysomelid leaf bee**

28(27). Pronotum (fig. 13) yellow with 2 or 3 black spots . .
28'. Pronotum black with yellow sides, elytra green
yellow with black markings (fig. 22). Cottonwoo
white willow. Adults present from June to Augu
Chrysomela scripta F. ..... **.cottonwood leaf bee**

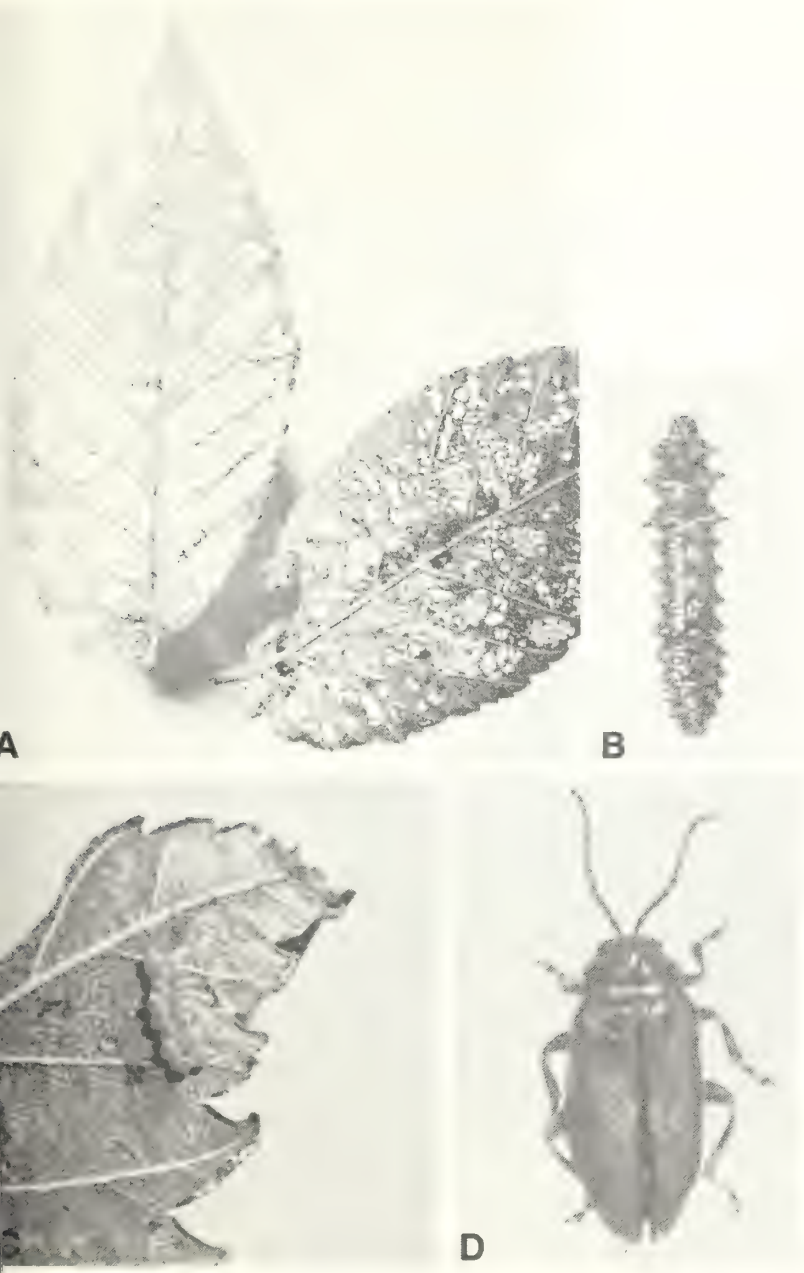
ure 22.—Cottonwood leaf beetle (*Chrysomela scripta*).

28). Pronotum yellow with 2 black spots, elytra yellow with a black stripe along the suture and lateral margin, a third stripe down center of elytra, head orange with black eyes (fig. 23). White willow. Adults active during August. *Disonycha alternata* (Illiger)
. . . . . **a chrysomelid leaf beetle**

9'. Pronotum yellow with 3 black spots, elytra yellowish green with black lateral stripe (fig. 24). American elm, Siberian elm. Adults active during May and August. *Pyrrhalta luteola* (Muller) . . . . . **elm leaf beetle**

A

Figure 23.—*Disonycha alternata*: A, adult, length 7-8 mm; adult defoliating willow.



igure 24.—Elm leaf beetle (*Pyrrhalta luteola*): A, skeletonized leaf; B, larva; C, eggs; D, adult, length 5-7 mm.

30(17). Hind legs yellowish brown to brown 31

30'. Hind legs red. American elm, Siberian elm, bur oak, Siberian peashrub (fig. 25), common lilac, American plum, tatarian honeysuckle. Present from August to September. *Melanoplus femurrubrum* (De Geer) .....**redlegged grasshopper**

31(30). Hind legs with black chevron markings, body brown. American elm, Siberian elm, Siberian peashrub (fig. 25), American plum, Russian-olive. Present from July to September. *Melanoplus sanguinipes* (F.) .....**migratory grasshopper**

31'. Hind legs without black chevron markings, body dark brown, two light tan longitudinal stripes from the head to tip of the wings. American elm, Siberian elm, American plum, Siberian peashrub (fig. 25), sand cherry, boxelder, Peking cotoneaster. Present from July to September. *Melanoplus bivittatus* (Say) .....**twostriped grasshopper**

Figure 25.—Defoliation of caragana by grasshoppers (*Melanoplu* spp.).

(16). Antennae short, less than half the body length, abdomen soft and fleshy 33

32'. Antennae long, equal to half the body length, abdomen sclerotized. Long slender insect with thin legs (fig. 26). Bur oak. Feeding from June to September. *Diapheromera femorata* (Say) ..... **walkingstick**

ure 26.—Walkingstick (*Diapheromera femorata*).

33(32). Prolegs absent on all abdominal segments. **Beetle larvae** 34

33'. Prolegs present on two or more abdominal segments **Sawflies, caterpillars** (figs. 7,27) 35

34(33). Larva black turning dull yellow with age, abdomina segments with 6 rows of spots (fig. 22). Cottonwood Larvae present during the summer. *Chrysomela scripta* F. . . . . **cottonwood leaf beetl**

34'. Larva yellow, body has black bands down the bac with setae between the bands (fig. 24). American elm Siberian elm. Larvae present from May to June *Pyrrhalta luteola* (Muller) . . . . . **elm leaf beetl**

35(33). Prolegs present on abdominal segments 2-8, 10 (fig 27). **Sawflies** 3

35'. Prolegs absent on abdominal segments 1, 2, 7, 8, and (fig. 7). **Caterpillars** 4

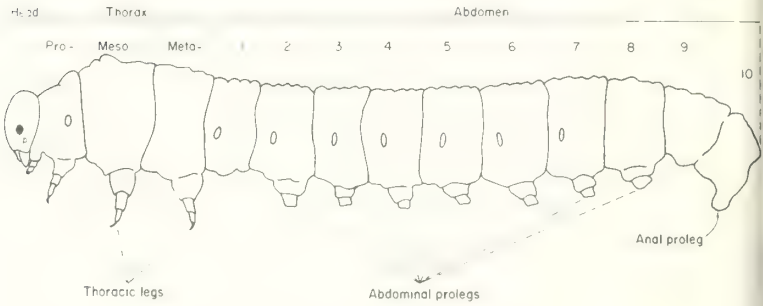


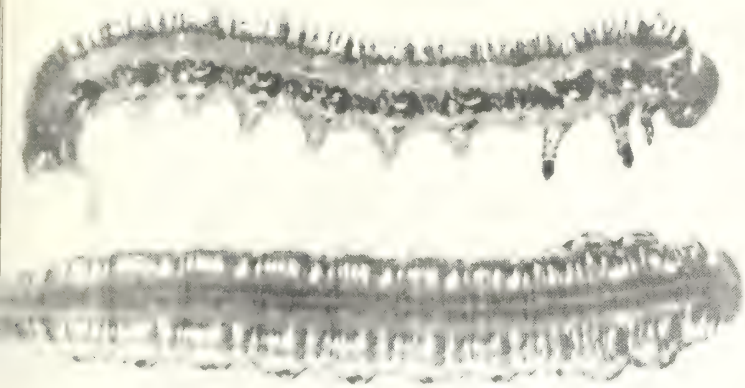
Figure 27.—Generalized drawing of a sawfly.

36(35). Head light brown, gray, offwhite, or yellowish orange . . . . . .

36'. Head dark brown or black . . . . . .

37(36). Head offwhite or light brown . . . . . .

37'. Head yellowish orange, body yellowish green with da green stripes down the back and sides (fig. 28). Wh spruce, blue spruce (plate 8). Larvae present from Ju to August. *Pikonema alaskensis* (Rohwer) . . . . . **yellowheaded spruce saw**



gure 28.—Yellowheaded spruce sawfly (*Pikonema alaskensis*).

(37). Head offwhite, body offwhite with black spiracles and black dorsal stripe (fig. 29). American elm, Siberian elm, white willow. Larvae present from July to September. *Cimbex americana* Leach . . . . . **elm sawfly**

38'. Head light brown with reddish-brown markings, body light green with whitish dorsal stripe. Each body segment outlined front and back with a definite white line. White willow. Larvae present from June to September, two or more generations per year. *Nematus mendicus* Walsh . . . . . **.a willow sawfly**

gure 29.—Elm sawfly (*Cimbex americana*) larva at rest on Siberian elm.

39(36). Body white 4
39'. Body yellowish green, dark green, gray or black 4

40(39). Thorax swollen, body translucent white (fig. 30). Hea
black. Bur oak. Larvae present from July to Augus
Caliroa sp. . . . . .**a slug sawfl**
40'. Thorax not swollen, body solid white. Head blac
(plate 2). Green ash. Larvae present from May to Jun
Tethida cordigera (Palisot de Beauvois)
. . . . . .**blackheaded ash sawfl**

Figure 30.—A slug sawfly (*Caliroa* sp.) skeletonizing th
underside of bur oak leaf.

1(39). Head brown 42
41'. Head black 43

2(41). Body grayish green with yellow spots and irregular rows of black dots. Tatarian honeysuckle. Larvae present from June to July. *Zaraea inflata* Norton ..... **honeysuckle sawfly**
42'. Body olive green due to secretion of slime. Thorax swollen (plate 3). American plum. Larvae present from June to July. *Caliroa cerasi* (L.) ..... **pearslug**

3(41). Feeds on willow, pine 44
43'. Feeds on tamarack, Siberian larch. Body yellowish green with dorsal gray band (plate 2). Larvae present from June to September. *Pristiphora erichsonii* (Hartig) ..... **larch sawfly**

igure 31.—Willow sawfly (*Nematus ventralis*) feeding on *Salix*.

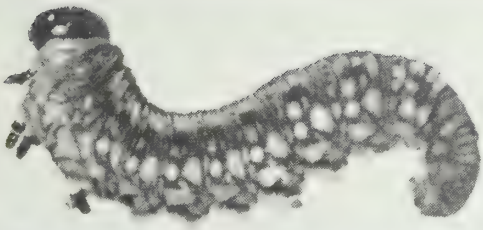
44(43). Body grayish or yellowish green 45

44'. Body dark brown to black, sides of each body segmen with yellow spots (fig. 31). Cottonwood, white willow Larvae present from June to July. *Nematus ventrali* Say . . . . . **willow sawfly**

45(44). Body grayish green with a light dorsal stripe; dark green stripe down the side with black patch on top o last body segment (fig. 32). Scotch pine, Austrian pine Larvae present from May to June. *Neodiprion sertife* (Geoffroy) . . . . . **European pine sawfly**

45'. Body yellowish green; sides mottled in black, tw black stripes down the back (fig. 33). Ponderosa pine Scotch pine. Larvae present from July to October *Diprion similis* (Hartig) . . . . . **introduced pine sawfly**

Figure 32.—European pine sawfly (*Neodiprion sertifer*): A, dorsa and lateral view of larvae; B, larvae defoliating Scotch pine.

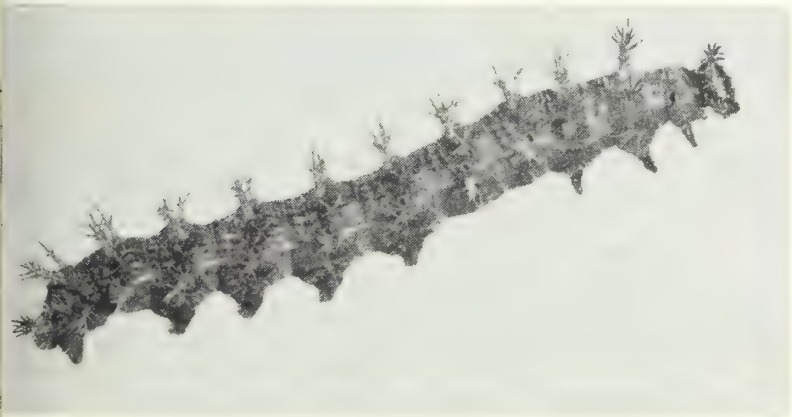


igure 33.—Lateral view of the introduced pine sawfly (*Diprion similis*).

4(35). Prolegs present on abdominal segments 3 and 4 (figs. 7, 34) 47
46'. Prolegs absent on abdominal segments 3 and 4 (fig. 51) 76

4'(46). Head with rough texture. Body may or may not have prominent spines or clubs 48
47'. Head with smooth texture. Body without prominent spines 51

8(47). Larvae have more than five body segments with prominent spines (fig. 34) 49
48'. Larvae have less than five body segments with prominent spines or clubs (fig. 36) 50



igure 34.—Violet tip caterpillar (*Polygonia interrogationis*).

49(48). Head orange with a pair of branched spines, bod
reddish brown with black-tipped orange spines (fig
34). American elm, Siberian elm. Larvae present durin
July. *Polygonia interrogationis* F. . **violet tip caterpilla**

49'. Head black with no spines, body black with blac
spines and a row of orange spots down the back (fig
35). Colonial feeder. American elm, Siberian elm
white willow. Larvae present from June to July
Nymphalis antiopa (L.) . . . . **mourningcloak butterfl**

Figure 35.—Mourningcloak butterfly (*Nymphalis antiopa*).

50(48). Clublike structures present on second thoracic s
ment, body yellowish brown or green with a wh
patch near center of back (fig. 36). Cottonwood, wh
willow. Larvae present from April to August. *Limeni*
archippus (Cramer) . . . . . **vicer**

50'. Clublike structures absent on second thoracic segme
body pale green with yellowish dorsal stripe edg
with blue and yellow. Head with branched "antler
Hackberry. Larvae present from June to Augu
Asterocampa celtis Boisduval & LeConte
. . . . . **hackberry caterpil**

ure 36.—Viceroy butterfly (*Limenitis archippus*).

(47). Body with long setae (hair) 52
1'. Body with short, sparse setae 61

(51) Head black, blue, or gray 53
2'. Head white marked with black. Body white with long white hair. Cottonwood, white willow, bur oak. Larvae present from August to September. *Acronicta leporina vulpina* (Grote) .....**a dagger moth**

(52). Body sparsely covered with long hair 54
3'. Body densely covered with long hair 56

(53). Head pale blue or gray 55
4'. Head black. Body black with a yellow cervical shield and yellow body stripes (plate 8; fig. 37). Colonial feeders. White willow, Saskatoon serviceberry, bur oak, American plum. Larvae present from July to September. *Datana ministra* (Drury)
.....**yellownecked caterpillar**

Figure 37.—Yellownecked caterpillar (*Datana ministra*): A, e
mass; B, mature larvae.

55(54). Head and body pale blue, body with keyhole shap
spots down the back (plate 6; fig. 38). Cottonwoo
green ash, Peking cotoneaster, basswood, aspen. Lar
present from April to June. *Malacosoma disstria*
Hübner . . . . . **forest tent caterpil**

55'. Head and body light gray, body depressed with h
fringe down each side (fig. 39). Metathorax (fig.
with black velvet band. White willow, green ash, l
oak, Siberian elm. Larvae present from June to Augu
Tolype velleda (Stoll) . . . . . **Velleda lappet m**

igure 38.—Forest tent caterpillar (*Malacosoma disstria*): A, larvae defoliating Peking cotoneaster; B, larvae on aspen.

Figure 39.—Velleda lappet moth (*Tolype velleda*).

56 (53). Long hair pencils present on 3rd abdominal segment (fig. 41) . . . . . 5'

56'. Long hair pencils absent on 3rd abdominal segment 5

57(56). Single black pencil on abdominal segments 1 and 3 5

57'. Pair of black pencils on abdominal segments 1 and 3 Single pencil on 8th abdominal segment, body pal yellow with pale yellow hair (fig. 40). Boxelde cottonwood, green ash, bur oak. Larvae present fro July to September. *Acronicta americana* (Harris) . . . . . **American dagger mot**

Figure 40.—American dagger moth (*Acronicta americana*).

(57). Body black and densely covered with reddish-brown hair, head black. Single black pencil on abdominal segments 1, 3, and 8 (plate 5; fig. 41). White willow, common chokecherry. Larvae present from July to September. *Acronicta dactylina* Grote
. . . . . **a dagger moth**

58'. Body white and densely covered with yellow hair, head black. Single black pencil on abdominal segments 1, 3–5, and 8. White willow, cottonwood. Larvae present from June to September. *Acronicta lepusculina* Guenée
. . . . . **cottonwood dagger moth**

ure 41.—A dagger moth (*Acronicta dactylina*).

56). Feeds on hardwoods 60
59'. Feeds on spruce. Head black, body with long pencils near head and tail, black and white tufts down each side, gray tufts on abdominal segments 1 to 4 (fig. 42). White spruce, blue spruce. Larvae present from June to July. *Dasychira* sp. . . . . **a spruce tussock moth**

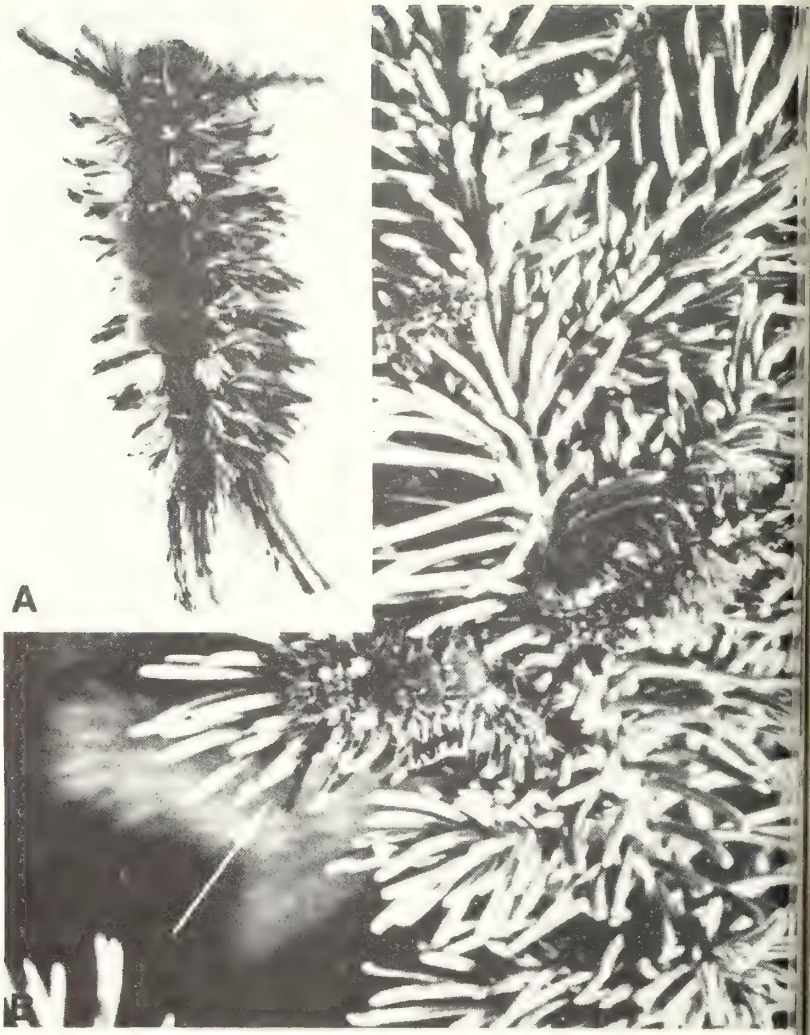
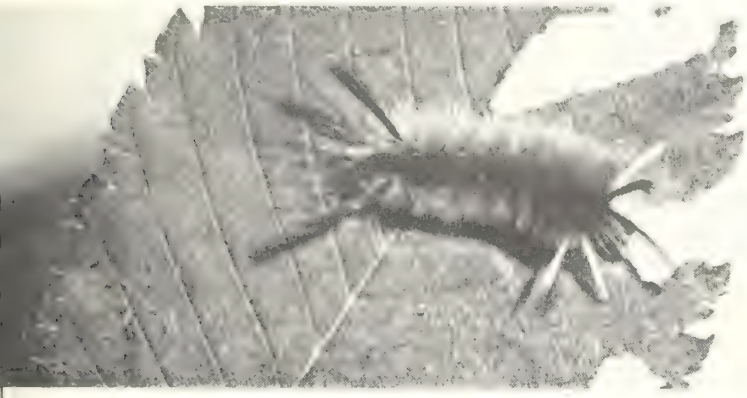


Figure 42.—A spruce tussock moth (*Dasychira* sp.): A, dor
view; B, feeding on spruce.

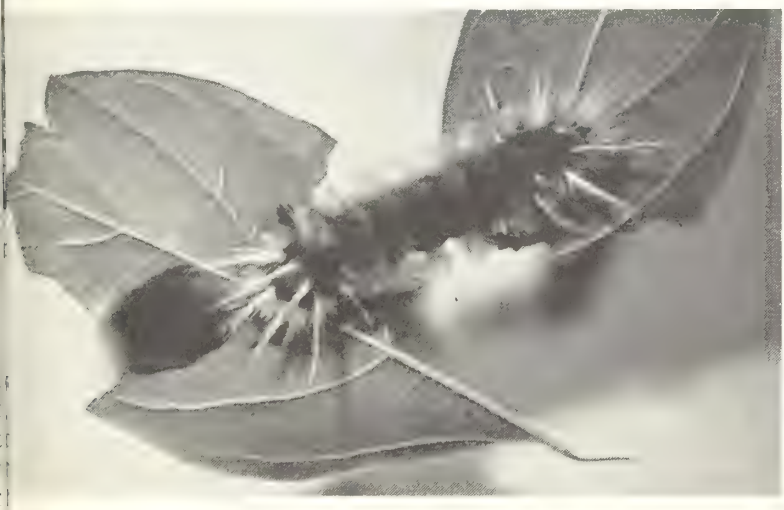
60(59). Body with olive tinged yellowish-gray hair, bl
pencils near head and tail. Head and body black (
43). American elm, Siberian elm, green ash, boxelc
bur oak, common chokecherry. Larvae present fr
July to September. *Halisidota tessellaris* (J. E. Smith
. . . . . **pale tussock m**

60'. Body with a row of black tufts down back and vellow tufts on side of abdominal segments 2—6 (fig. 44), longer tufts near head and tail. Head and body black. Boxelder, white willow, green ash, common chokecherry. Larvae present from July to October. *Halisidota maculata* (Harris) . . . .**spotted tussock moth**

(51). Larvae with tubercles, filaments, or dorsal humps . .62
61'. Larvae without tubercles, filaments, or dorsal humps 73



gure 43.—Pale tussock moth (*Halisidota tessellaris*).



ure 44.—Spotted tussock moth (*Halisidota maculata*).

62(61). Caudal horn or spinelike process present on 8
abdominal segment . . . . . .(
62'. Caudal horn or spinelike process absent on 8
abdominal segment . . . . . .(

63(62). No scoli present on thoracic segments . . . . . .
63'. Two pair of scoli present on thoracic segments, he
and body bluish green (plate 5). American elm, gre
ash. Larvae present from July to September. *Ceraton*
amyntor (Hübner) . . . . . **elm sphi**

64(63). Head yellowish green with red and yellow stripe. Bo
yellowish green marked with seven oblique purpl
stripes edged below with white, caudal horn bla
above and yellow below. American plum, comm
chokecherry, sand cherry, hackberry. Larvae pres
from July to September. *Sphinx drupiferarm* Abbo
& Smith . . . . . **hackberry sph**
64'. Head bluish green with light green stripe. Body li
green with seven oblique yellow stripes edged ab
with bluish green, caudal horn pale blue. Green a
common lilac. Larvae present from July to Septeml
Sphinx chersis (Hübner) . . . . . **great ash sph**

65(62). Dorsal hump present on 8th abdominal segment . .
65'. Dorsal hump absent on 8th abdominal segment . . .

66(65). Head orange or reddish orange . . . . . .
66'. Head yellow, body pink to gray with three black dc
lines. Reddish-orange enlargement on 8th abdon
segment (plate 1). Bur oak. Larvae present f
August to October. *Symmerista albifrons* (J. E. Sm
. . . . . **.redhumped oak**

67(66). Body yellowish with five black dorsal lines, l
orange. Orange enlargement on 8th abdominal
ment. Bur oak. Larvae present from June
September. *Symmerista canicosta* Franclemont
. . . . . **a redhumped oakw**
67'. Body pink to gray with five black dorsal lines,
reddish orange. Reddish-orange enlargement on
abdominal segment. Bur oak. Larvae present
August to October. *Symmerista albicosta* (Hübner)
. . . . . **.a redhumped oakw**

65). Prominent projections (scoli) present on one or more thoracic segments 69

8'. Prominent projections absent on all thoracic segments (fig. 7) 70

68). Head bluish green shaded with brown. Body light green with six pink or green tubercles per segment. White willow, American elm, Siberian elm, paper birch. Larvae present from July to September. *Actias luna* (L.) ..... **luna moth**

9'. Head yellowish green with two black spots. Body green with four coral-red tubercles on thoracic segments, two rows of yellow tubercles down the back, and two rows of blue tubercles down each side. White willow, green ash, boxelder, common lilac, common chokecherry. Larvae present from June to October. *Hyalophora cecropia* (L.) ..... **cecropia moth**

68). Dorsal projection or hump present on 1st abdominal segment 71

0'. Dorsal projection or hump absent on 1st abdominal segment. Head reddish brown. Body green with orange spiracles, orange or gold tubercles with a silvery tint on each segment, last body segment edged with purple (plate 1). White willow, cottonwood, American elm, Siberian elm, basswood, paper birch. Larvae present from June to October. *Antheraea polyphemus* (Cramer). ..... **polyphemus moth**

70). Head green 72

'. Head purple with dark lines. Body reddish brown and marked with two oblique white stripes, bifurcate dorsal projections with a spine on each point (fig. 45). White willow, boxelder, paper birch. Larvae present from July to September. *Schizura ipomoeae* Doubleday ..... **false unicorn caterpillar**

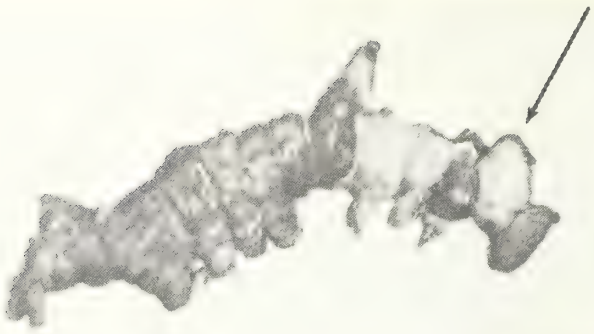


Figure 45.—False unicorn caterpillar (*Schizura ipomoeae*) start to molt (note old head capsule).

72(71). Body bluish green with dorsal projections on abdominal segments. Head pale green with four wh and two black lines. American elm, Siberian e Larvae present from June to September. *Ne bidentata* Walker . . . . . **serrated elm caterpi**

72'. Body variegated white and brown with a dorsal pro tion on 1st abdominal segment (fig. 46). Mesotho and metathorax (fig. 7) are green. Head green brown. American elm, Siberian elm, white will common chokecherry. Larvae present from July September. *Schizura unicornis* (J. E. Smith) . . . . . **unicorn caterp**

Figure 46.—Unicorn caterpillar (*Schizura unicornis*).

(61). Head green, dark brown, black 74
73'. Head orange, reddish brown 75

(73). Spruce needles clipped and webbed together. Head dark brown or black, body pale yellow to dark brown with yellowish hair-bearing tubercles. Larvae present from bud break until June. *Choristoneura biennis* Freeman (plate 3). . . . . **two-year-cycle budworm**
Choristoneura fumiferana (Clemens)
. . . . . **spruce budworm**

74'. Hardwood leaves defoliated. Head green with red lateral stripe, body green to yellowish green with reddish-purple saddle-shaped patch on abdominal segments 3, 4, and 5. American elm, Siberian elm, white willow, common chokecherry, paper birch. Larvae present June to September. *Heterocampa guttivitta* (Walker) . . . . . **saddled prominent**

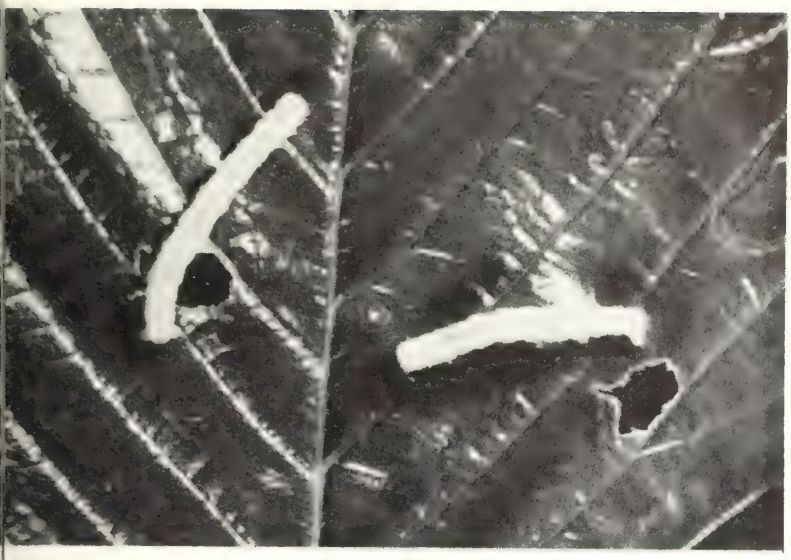
(73). Head orange with black and white lateral stripes. Body yellowish green with reddish-brown band bordered by a yellow stripe from base of head to the last abdominal segment (fig. 47). American elm, Siberian elm, bur oak, paper birch. Larvae present from July to September. *Heterocampa manteo* (Doubleday)
. . . . . **variable oakleaf caterpillar**

75'. Head reddish brown, body yellowish green with reddish-brown band from the head to the 8th abdominal segment. Anal prolegs modified into tails. Willow. Larvae present from July to September. *Cerura* prob. *scolopendrina* (Boisduval) . . . . .**a twotailed caterpillar**

(46). Prolegs on abdominal segment 6, absent from segment 5 77

76'. Prolegs on abdominal segments 5 and 6, rudimentary pair on 5th segment. Body varies from brown to green with three white lines above spiracles and a yellow line below (fig. 48). American elm, Siberian elm, American plum, green ash, boxelder, common chokecherry. Larvae present from May to June. *Alsophila pometaria* (Harris) . . . . . **fall cankerworm**

Figure 47.—Variable oakleaf caterpillar (*Heterocampa mante*
A, defoliation; B, larva (light phase); C, larvae (d
phase).



gure 48.—Fall cankerworm (*Alsophila pometaria*).

(76). Head round or slightly notched 78
7'. Head deeply notched with blunt projections. Body brown to gray with short filaments on undersurface of abdominal segments 7 and 8 (plate 2; fig. 49). White willow, boxelder, tamarack, larch, paper birch, aspen. Larvae present from July to August. *Biston cognataria* (Guenée). . . . . **pepper-and-salt moth**

gure 49.—Pepper-and-salt moth (*Biston cognataria*): A, larva; B, notched head.

78(77). Head dark brown 79

78'. Head yellow, body yellow with ten longitudinal black lines (plate 7). American elm, Siberian elm, sand cherry, boxelder, American plum. Larvae present from May to July. *Erannis tiliaria* (Harris) . . . **linden looper**

79(78). Abdominal segments 2 and 3 with projections or swollen ridges 80

79'. Abdominal segments 2 and 3 without projections or swollen ridges. Body light brown to black with a yellow stripe below spiracles (plate 1, fig. 50). American elm, Siberian elm, American plum, boxelder, green ash, apple. Larvae present from May to July. *Paleacrita vernata* (Peck) .....**spring cankerworm**

Figure 50.—Spring cankerworm (*Paleacrita vernata*): A, damag to single row Siberian elm shelterbelt; B, larvae hav consumed everything but leaf petioles.

0(79). First abdominal segment less than combined length of thoracic segments (fig. 7). 81

80'. First abdominal segment equal to length of thoracic segments. Body light to dark brown with a raised transverse ridge on abdominal segments 2, 5, and 8 (fig. 51). American elm, Siberian elm. Larvae present from June to July. *Ennomos subsignarius* (Hübner)
. . . . . **elm spanworm**

igure 51.—Elm spanworm (*Ennomos subsignarius*) feeding on American elm (note transverse ridge on abdominal segments 2, 5, and 8).

1(80). Body mottled brown, abdominal segments 2 and 3 with a pair of white tipped filaments. American elm, Siberian elm. Larvae present from June to July. *Nematocampa limbata* (Haworth) . . . . **filament bearer**

81'. Body reddish brown and covered with coarse rugosities, abdominal segments 2 to 4 with winged lateral projections. American elm, Siberian elm. Larvae present from July to August. *Nemoria* sp.
. . . . . **a winged looper**

INSECT DEFOLIATORS, BY FEEDING CHARACTERISTICS

C = gregarious or colonial defoliators, F = leaffolders, R = leafrollers, S = solitary defoliators, W = webworms

Insect	American elm	American plum	Boxelder	Bur oak	Choke-cherry	Cotton-wood	Green ash	Ponderosa pine	Siberian elm	Siberian peashrub	White willow
Acrobasis sp (a leafrolling moth)				R							
Veronicta americana (American dagger moth)			S	S		S	S				
Veronicta dactylina (a dagger moth)					S						S
Veronicta leporina vulpina (a dagger moth)				S		S					S
Veronicta lepusculina (cottonwood dagger moth)						S					S
Actias luna (luna moth)	S								S		S
Alsophila pometaria (fall cankerworm)	S	S	S		S	S	S		S		
Altica plicipennis (a chrysomelid leaf beetle)					S						S
Antheraea polyphemus (polyphemus moth)	S								S		S
Archips argyrospilus (fruittree leafroller)							F				
Archips cerasivoranus (uglynest caterpillar)					W						
Biston cognataria (pepper-and-salt moth)			S								S
Caltroa cerasi (pearslug)		C									

C = gregarious or colonial defoliators, F = leaffolders, R = leafrollers, S = solitary defoliators, W = webworms

Insect	American elm	American plum	Boxelder	Bur oak	Choke-cherry	Cotton-wood	Green ash	Ponderosa pine	Siberian elm	Siberian peashrub	White willow
Caltroa sp (a slug sawfly)				C							
Canarsia ulmiarrosorella (a leaf tieing-moth)	W										
Cecidomyia sp (a leaffolding fly)				F							
Ceratomia amyntor (elm sphinx)	S						S		S		
Cerura scolopendrina (a twotailed caterpillar)									S		
Chrysomela scripta (cottonwood leaf beetle)						S					S
Cimbex americana (elm sawfly)	S								S		S
Cotalpa lanigera (goldsmith beetle)						S		S			S
Datana ministra (yellownecked caterpillar)	C			C							C
Diapheromera femorata (walkingstick)				S							
Dichelonyx subvittata (a June beetle)	S			S	S		S		S		S
Diprion similis (introduced pine sawfly)								S			
Disonycha alternata (a chrysomelid leaf beetle)											S

INSECT DEFOLIATORS, BY FEEDING CHARACTERISTICS

C = gregarious or colonial defoliators, F = leaffolders, R = leafrollers, S = solitary defoliators, W = webworms

Insect	American elm	American plum	Boxelder	Bur oak	Choke-cherry	Cotton wood	Green ash	Ponderosa pine	Siberian elm	Siberian peashrub	White willow
Ennomos subsignarius (elm spanworm)	S								S		
Epicauta fabricii (ashgray blister beetle)										S	
Epicauta subglabra (caragana blister beetle)										S	
Erannis tiliaria (linden looper)	S								S		
Halisidota maculata (spotted tussock moth)			S		S		S				S
Halisidota tessellaris (pale tussock moth)	S		S	S	S		S				
Heterocampa guttivitta (saddled prominent)	S				S				S		S
Heterocampa manteo (variable oakleaf caterpillar)	S			S					S		
Hyalophora cecropia (cecropia moth)			S		S		S				S
Hyphantria cunea (fall webworm)	W	W			W	W				W	W
Itonida sp (a leaffolding fly)				F							
Lepyrus palustris (a weevil)	S								S		
Limenitis archippus						S					S

C = gregarious or colonial defoliators, F = leaffolders, R = leafrollers, S = solitary defoliators, W = webworms

Insect	American elm	American plum	Boxelder	Bur oak	Choke-cherry	Cotton-wood	Green ash	Ponderosa pine	Siberian elm	Siberian peashrub	White willow
Lytta nuttalli (Nuttall blister beetle)										S	
Magdalis armicollis (red elm bark weevil)	S								S		
Magdalis barbita (black elm bark weevil)	S								S		
Malacosoma americanum (eastern tent caterpillar)					W						
Malacosoma californicum lutescens (prairie tent caterpillar)					W		W				
Malacosoma disstria (forest tent caterpillar)				C	C	C					
Melanoplus bivittatus (twostriped grasshopper)	S	S	S							S	
Melanoplus femurrubrum (redlegged grasshopper)	S	S		S					S	S	
Melanoplus sanguinipes (migratory grasshopper)	S	S							S	S	
Nematocampa limbata (filament bearer)	S								S		
Nematus mendicus (a willow sawfly)											S
Nematus ventralis (willow sawfly)						S					S
Nerice bidentata (serrated elm caterpillar)	S										S

INSECT DEFOLIATORS, BY FEEDING CHARACTERISTICS

C = gregarious or colonial defoliators, F = leaffolders, R = leafrollers, S = solitary defoliators, W = webworms

Insect	American elm	American plum	Boxelder	Bur oak	Choke-cherry	Cotton-wood	Green ash	Ponderosa pine	Siberian elm	Siberian peashrub	White willow
Neotoma inconspicua (plum webspinning sawfly)		W									
Nymphalis antiopa (mourning cloak butterfly)	C								C		C
Paleacrita vernata (spring cankerworm)	S	S	S				S		S		
Phyllocolpa bozemani (poplar leaffolding sawfly)						F					
Polygonia interrogationis (violet tip caterpillar)	S								S		
Polyphylla decemlineata (tenlined June beetle)											S
Polyphylla hammondi (a June beetle)											S
Psorosina hammondi (appleleaf skeletonizer)	R										
Pyrrhalta luteola (elm leaf beetle)	S								S		
Schizura ipomoeae (false unicorn caterpillar)			S								S
Schizura unicornis (unicorn caterpillar)	S				S				S		S
Sphinx chersis (great ash sphinx)							S				
Sphinx drupiferarm											

INSECT DEFOLIATORS: BY HABITAT

G = gregarious or colonial defoliators, F = leaffolders, R = leafrollers, S = solitary defoliators, W = webworms

Insect	American elm	American plum	Boxelder	Bur oak	Choke-cherry	Cotton-wood	Green ash	Ponderosa pine	Siberian elm	Siberian peashrub	White willow
Symmerista albicosta (a redhumped oakworm)				G							
Symmerista albifrons (redhumped oakworm)				G							
Symmerista canicosta (redhumped oakworm)				G							
Tethida cordigera (blackheaded ash sawfly)							G				
Tolype velleda (Velleda lappet moth)	S			S			S				S

Galls appear as abnormal woody growths or swellings on twig and branches, closed leaf galls, warty eruptions on the leaf blad rosette-type leaf clusters, or abnormal fruit development.

1. Damage on deciduous trees and shrubs . . . . .
1'. Damage on spruce. Galls on twig tips. June. *Adelg abietis* (L.) . . . . . .eastern spruce gall aph

2(1). Damage on:
Willow . . . . .
Hackberry . . . . .
Green ash 1
Boxelder, silver maple 1
Elm . . . . . .
Cottonwood . . . . . .
American plum . . . . . .
Common chokecherry . . . . . .
Bur oak . . . . . .
Rose . . . . . .

3(2). Leaf galls . . . . . .
3'. Twig and branch galls . . . . . .

4(3). Leaves stunted . . . . . .
4'. Leaves not stunted . . . . . .

5(4). Terminal growth with one pine conelike gall (fig. 5
Willow. Summer. *Rhabdophaga strobiloides* (Osten Sacken) . . . . . .**pine cone**
5'. Terminal growth with 2 to 5 pine conelike ga
Willow. Summer. *Rhabdophaga racemi* Felt
. . . . . **clustered willow**

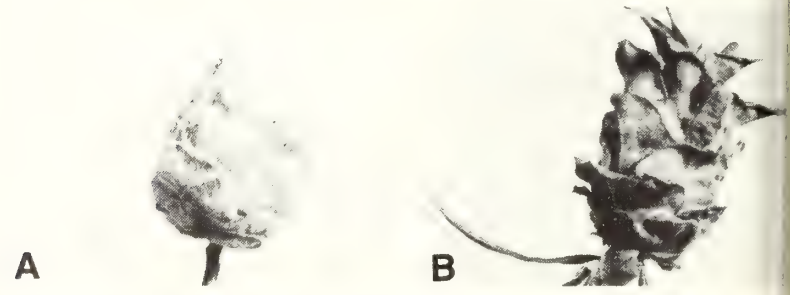
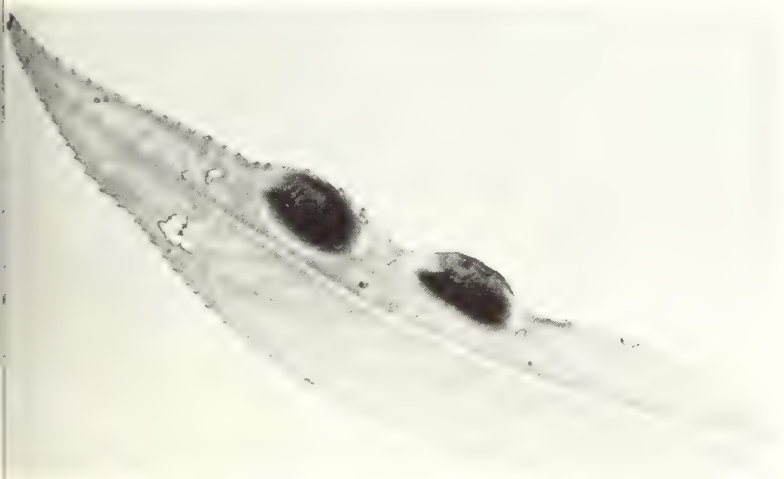


Figure 52.—Pine cone gall (*Rhabdophaga strobiloides*): A, ga *Salix alba* (length 25-40 mm); B, gall on *Salix* sp.

4). Smooth spherical gall, yellow with red tinge (fig. 53). Willow. June to October. *Pontania hospes* (Walsh) . . . . . **willow apple gall**

5'. Rough flat-ovoid gall, yellowish green to red (fig. 54). Willow. June to October. *Pontania proxima* (Lepeletier) . . . . . **bean gall sawfly**

gure 53.—Willow apple gall (*Pontania hospes*) on *Salix* sp. (diameter 8-12 mm). This gall is synonymous with *P. pomum*.



gure 54.—Bean gall sawfly (*Pontania proxima*) on willow. This species has two or more generations per year.

7(3). Gall on current season's growth . . . . . .

7'. Gall not on current season's growth. Gall wi
diameter of 2 inches or less and encircling the bran
Serpentine tunnels packed with granular frass, e
hole at bottom edge of gall. Branch dies. Willo
Adults (fig. 55) present in June.
Agrilus politus (Say) . . . . . .**a flatheaded wood bo**
Agrilus criddlei Frost . . . . . .**a flatheaded wood bo**

Figure 55.—A flatheaded willow borer (*Agrilus criddlei*).

8(7). Single larval chamber, narrowly oval gall. Termi
twig beyond gall dies and forms a beak (fig. 5
Willow. Summer. *Mayetiola rigidae* (Osten Sacken)
. . . . . **willowbeaked gall mi**

8'. Multiple larval chambers, potato type gall (fig. 5
Willow. Summer. *Euura* sp. . . . . .**a sawfly twig**

Figure 56.—Willowbeaked gall midge (*Mayetiola rigidae*): A, ll
on *Salix alba*; B, gall on *Salix* sp.

gure 57.—*Euura* sp. on willow twig.

2). Leaf gall 10
9'. Terminal bud slightly enlarged, 2 to 3 larval chambers. Hackberry. Summer. *Pachypsylla gemma* Riley ..... **hackberry bud gall**

)(9). Gall on leaf blade 11
10'. Gall on midvein, light tan to dark brown, kidney shaped (fig. 58). Hackberry. Summer. *Pachypsylla venusta* Osten Sacken ..... **hackberry petiolegall**

Figure 58.—Hackberry petiolegall (*Pachypsylla venusta*), le
10-20 mm.

11(10). Yellow blister gall on upper leaf surface, small b
point in the center, irregular to circular in out
Hackberry. Summer. *Pachypsylla celtidisvesicula* H
. . . . . **hackberry blister**

11'. Light green mammiform gall on lower leaf surface
59). Cup-shaped depressions on upper leaf sur
Hackberry. Summer. *Pachypsylla celtidismamma*
(Riley) . . . . . **hackberry nipplegall m**

gure 59.—Hackberry nipplegall maker (*Pachypsylla celtidis-mamma*), length 8 mm.

(2). Found on buds and leaves 13
12'. Found on staminate flowers; distorted lobulate galls which may or may not be produced on stalks (fig. 60). Green ash. Spring. *Eriophyes fraxiniflora* Felt
..... **ash flower gall mite**

Figure 60.—Ash flower gall mite (*Eriophyes fraxiniflora*): showing the difference between normal male flow (1) and those attacked by mites (2); B, galls flower stalks; C, leaves attacked by mites.

ure 60C.—Leaves attacked by mites.

(12). Found on the midvein 14
.3'. Found on the leaf blade 15

(13). Spherical gall on upper surface (fig. 61). One larva per gall. Green ash. June to September. *Cecidomyia pellex* Osten Sacken ..... **ash bullet gall**

.4'. Pouch-type midrib gall with exit on upper leaf surface (fig. 62). Numerous larvae per gall. Green ash. Early summer. *Contarinia canadensis* Felt . . . **ash midrib gall**

Figure 61.—Ash bullet gall (*Cecidomyia pellex*) on midvein green ash.

Figure 62.—Ash midrib gall (*Contarinia canadensis*).

5(13). Beadtype gall (fig. 63) that protrudes from both surfaces of the leaf blade. Green ash. Summer. *Aceria chrondriphora* Keifer . . . . . **a beadtype gall mite**

15'. Distorted and tightly rolled leaves 2 to 3 inches in diameter (fig. 60), unstalked lobulate galls. Green ash. Summer. *Eriophyes fraxinifiora* Felt . . . . . **ash flower gall mite**

igure 63.—*Aceria chrondriphora* on the leaf blade of green ash.

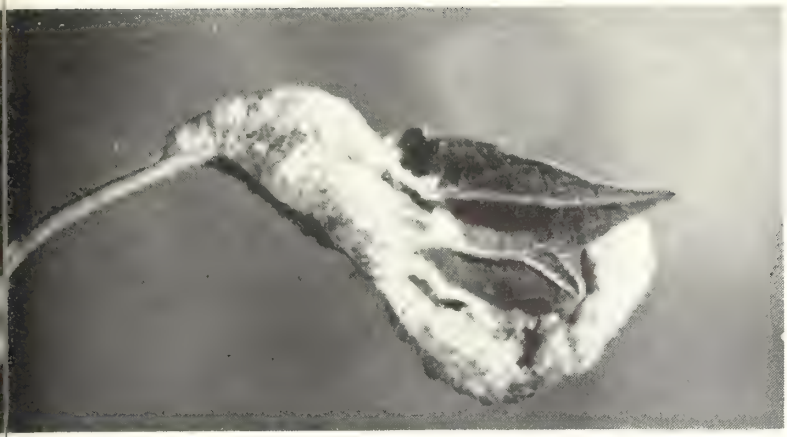
6(2). Leaf gall 17

16'. Twig gall, gradual swelling with entrance hole in bottom half (fig. 64). Boxelder. May to July. *Proteoteras willingana* (Kearfott) . . . . . **boxelder twig borer**

Figure 64.—Boxelder twig borer (*Proteoteras willingana*): mature gall with entrance hole on the right (len 20-40 mm), previous year's gall on the left; B, fr attack with exposed frass.

17(16). Found on boxelder . . . . . .
17'. Found on silver maple . . . . . .

18 (17). Galls on upper leaf surface . . . . . .
18'. Midrib gall on lower leaf surface. Enlarged pouch-ty gall with exit on upper leaf surface (fig. 65). Numer maggots per gall. Boxelder. June to August. *Dasine communis* Felt . . . . . **gouty vein g**



gure 65.—Gouty vein gall (*Dasineura communis*) on boxelder (length 10-25 mm).

(18). Hemispherical galls on midvein (fig. 66), light green with bluish tint. Boxelder. June to September. *Contarinia negundifolia* Felt . . . . . **boxelder leafgall**

9'. Warty swellings on leaf surface (fig. 67), white or brown leaf pile (hair) underneath. Boxelder. Summer. *Aceria negundi* Hodgkiss . . . . . **.warty leafgall**

gure 66.—Boxelder leafgall (*Contarinia negundifolia*), diameter 2 mm, height 3-5 mm.

Figure 67.—Warty leafgall (*Aceria negundi*) on boxel
(diameter 3-5 mm).

20(17). Warty swellings on upper leaf surface (fig. 68), red
green. Silver maple. Summer. *Vasates quadripedes*
(Shimer) . . . . . **maple bladdergall m**

20'. Pile (hair) on upper leaf surface, pink. Silver ma
Summer. *Aceria* sp . . . . . **a bladdergall m**

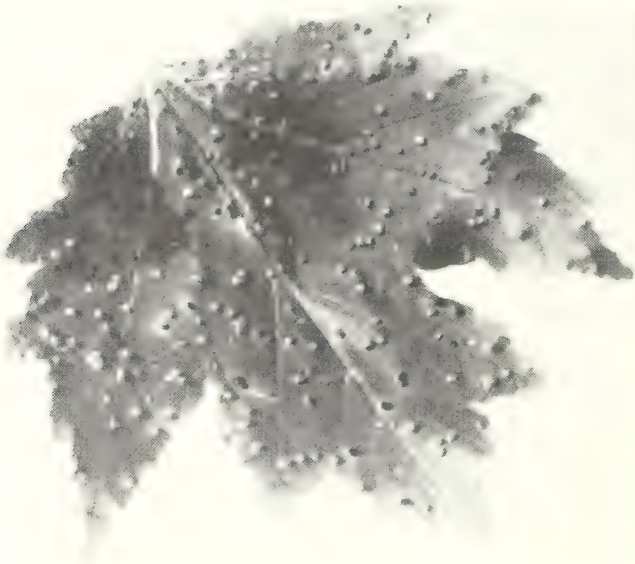


Figure 68.—Maple bladdergall mite (*Vasates quadripedes*).

1(2). Found on American elm 22
21'. Found on Siberian elm. Spindle-shaped gall on upper leaf surface, light green. Summer. *Aceria* sp . ..... **a finger gall mite**

2(21). Leafgall 23
22'. Twiggall, knotty growth. American elm. Summer. *Eriosoma rileyi* (Thomas) ..... **woolly elm bark aphid**

3(22). Coxcomb-shaped ridges between veins on upper leaf surface. Green aphids with brown or black legs. American elm. June to July. *Colopha ulmicola* (Fitch) ..... **elm cockscombgall aphid**
23'. Spindle-shaped gall on upper leaf surface (fig. 69). American elm. Summer. *Aceria ulmicola* (Nalepa) ..... **elm leaf gall**

Figure 69.—Elm leafgall (*Aceria ulmicola*) on American elm.

2(2). Leafgall 25
24'. Bud or twiggall 27

2(24). Damage on petiole 26
25'. Damage on leaf blade. Fleshy convoluted leaves (fig. 70). Aphids are green with dusky gray head and legs. Cottonwood. May to July. *Mordwilkoja vagabunda* (Walsh) ..... **poplar vagabond aphid**

Figure 70.—Poplar vagabond aphid (*Mordwilkoja vagabunda*).

26(25). Round gall formed by petiole only, transverse exit s
(fig. 71). Cottonwood. June to September. *Pemphig*
populitransversus Riley . . . . . **poplar petiolegall aph**
26'. Round gall formed by swelling and twisting of tl
petiole and leaf blade, angular exit slit (fig. 7
Cottonwood. June to September. *Pemphigus popu*
caulis Fitch . . . . . **poplar leaf-petiolegall aphi**

ure 71.—Poplar petiolegall aphid (*Pemphigus populitransversus*) on cottonwood; diameter 12-19 mm with a transverse exit slit.

ure 72.—Poplar leaf-petiolegall aphid (*Pemphigus populicaulis*). Gall diameter is 10-13 mm with a twisted angular exit slit.

27(24). Twig gall . . . . . .

27'. Blasted enlarged buds, minute aborted leaves (fig. 7
Cottonwood. May to July. *Aceria parapopuli* Keifer
. . . . . **poplar bud gall m**

Figure 73.—Poplar bud gall mite (*Aceria parapopuli*).

28(27). Round gall formed on current twig growth (fig. 74
base of petiole, transverse exit slit. Cottonwood.
to August. *Pemphigus populiramulorum* Riley
. . . . . **poplar twiggall a**

28'. Oval or oblong gall on current twig growth, round
hole (fig. 75). Cottonwood, aspen. Summer. *Mel*
gromyza schineri (Giraud) . . . . . **poplar twiggal**

ure 74.—Poplar twiggall aphid (*Pemphigus populiramulorum*).

ure 75.—Poplar twiggall fly (*Melanagromyza schineri*).

29(2). Spindle-shaped gall on upper leaf surface (fig. 76), to light green. American plum, common chokecher Summer. *Eriophyes emarginate* Keifer . . . . . a finger gall m

29'. Spindle-shaped gall on lower leaf surface (fig. 77), li green. American plum. Summer. *Eriophyes cer crumena* Walsh . . . . . .a finger gall m

Figure 76.—*Eriophyes emarginate* on plum; diameter 2 length 5-8 mm.

ure 77.—*Eriophyes cerasi-crumena* on plum; diameter 2 mm, length 8-13 mm.

(2). Spindle-shaped gall on upper leaf surface (fig. 76). Common chokecherry, American plum. Summer. *Eriophyes emarginate* Keifer . . . . . **.a finger gall mite**

0'. Fleshy and enlarged fruit (fig. 78), abortive seed, orange maggots present until fruit drops. Common chokecherry. May to September. *Contarinia virginianiae* (Felt) . . . . . **chokecherry midge**

Figure 78.—Chokecherry midge (*Contarinia virginianiae*) cau premature dropping of fruit.

31(2). Leaf gall .....

31'. Twig gall. Light tan globular woody gall with a rc surface, found in groups of 3 or more (fig. 79). oak. Summer. *Disholcaspis quercusmamma* (Walsh) ..... **oak bullet**

32(30). Rosette-type gall .....

32'. Woolly, spherical, or blister-type gall .....

ure 79.—Oak bullet gall (*Disholcaspis quercusmamma*) on bur oak. Freshly emerged female on gall.

(31). Distorted rosette-type leaves less than ½ inch in length, 1 to 3 larval chambers present. Bur oak. Spring and summer. *Cynips* sp. . . . . **an oak rosette gall**

3'. Circular arrangement of rosette leaflets on midvein, 1 to 5 larval chambers present. Bur oak. Early summer. *Andricus foliosus* Weld . . . . . **June gall wasp**

(31). Gall attached to leaf blade or veins 35

4'. Globose gall broadly attached to the petiole or midrib at base of leaf (fig. 80), smooth, multiple larval chambers. Bur oak. Summer. *Andricus petiolicola* (Osten Sacken) . . . . . **oak petiolegall**

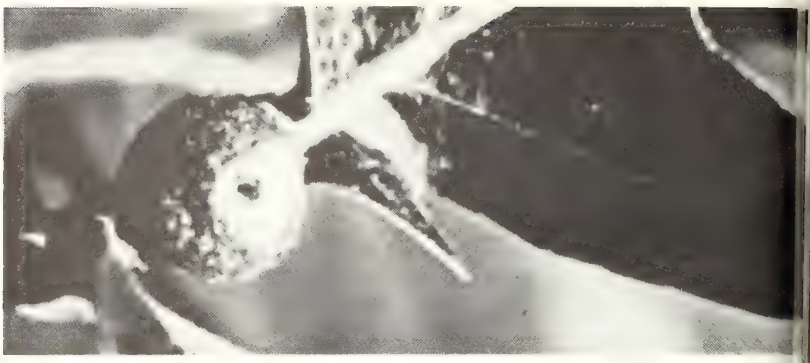


Figure 80.—Oak petiolegall (*Andricus petiolicola*). This gall c
also be located on the midrib.

35(33). Galls on lower leaf surface . . . . . .
35'. Galls on upper leaf surface. Blister-type galls vary fr
yellow to red with brown pile (hair) inside opening
lower leaf surface (fig. 81). Bur oak. Summer. *Ace*
querci (Garman) . . . . . **a blister gall m**

Figure 81.—A blister gall mite (*Aceria querci*) on bur oak.

(35). Woody gall has facets with or without spines 37
36'. Dense woolly gall has white or red pile (fig. 82a). Attached to the vein. Larval cells resemble kernels (fig. 82b). Bur oak. Summer and fall. *Andricus ignotus* (Bassett) . . . . . **woolly oak gall**

Figure 82.—Woolly oak gall (*Andricus ignotus*): A, woolly hair covering several kernel shaped larval cells; B, larval cells exposed showing exit holes.

37(36). Gall light brown. Crisscrossed cracks resulting spineless facets (fig. 83). Bur oak. Summer. *Acra macrocarpae* Bassett ..... **jewel oak**

37'. Gall light tan. Crisscrossed fissures resulting in conel projections with spines (fig. 84). Bur oak. Summ *Acraspis villosa* Gillette ..... **hairy oak**

Figure 83.—Jewel oak gall (*Acraspis macrocarpae*).

Figure 84.—Hairy oak gall (*Acraspis villosa*).

(2). Leaf gall 39

8'. Stem gall, green to reddish brown with sparse short spines. Numerous larval chambers. Rose. Summer. *Diplolepis spinosa* (Ashmead) ..... **rose twiggall**

(37). Spiked gall, yellow with red tinge, on lower leaf surface. Rose. Summer. *Diplolepis bicolor* (Harris) ..... **spiny rose gall**

9'. Pine conelike gall on terminal growth (fig. 85). Rose. Summer and fall. *Rhabdophaga rosacea* Felt ..... **rosette midge**

ıre 85.—Rosette midge (*Rhabdophaga rosacea*).

INSECT AND MITE GALLS, BY POINT OF ATTACK

B = buds, L = leaves, T = twigs

Insect	American elm	American plum	Boxelder	Bur oak	Choke-cherry	Cotton-wood	Green ash	White willow	Hackberry
Aceria chrondriphora (a beadtype gall mite)							L		
Aceria negundi (warty leafgall)			L						
Aceria parapopuli (poplar bud gall mite)						B			
Aceria quercia (a blister gall mite)				L					
Acraspis macrocarpae (jewel oak gall)				L					
Acraspis villosa (hairy oak gall)				L					
Andricus foliosus (June gall wasp)				L					
Andricus ignotus (woolly oak gall)				L					
Andricus petiolicola (oak petiolegall)				L					
Cecidomyia pellex (ash bullet gall)							L		
Colopha ulmicola	L								

	elm	plum	Boxelder	oak	cherry	wood	ash	willow	Hackberry
Contarinia negundifolia (boxelder leafgall)			L						
Cynips sp. (an oak rosette gall)				B					
Dasineura communis (gouty vein gall)			L						
Disholcaspis quercusmamma (oak bullet gall)				T					
Eriophyes cerasi-crumena (a finger gall mite)		L							
Eriophyes emarginate (a finger gall mite)		L			L				
Eriophyes fraxiniflora (ash flower gall mite)							B		
Eriosoma rileyi (woolly elm bark aphid)	T								
Euura sp. (a sawfly twiggall)								T	
Mayetiola rigidae (willowbeaked gall midge)								T	
Melanagromyza schineri (poplar twiggall fly)						T			
Mordwilkoja vagabunda (poplar vagabond aphid)						L			

INSECT AND MITE GALLS, BY POINT OF ATTACK

B = buds, L = leaves, T = twigs

Insect	American elm	American plum	Boxelder	Bur oak	Choke-cherry	Cotton-wood	Green ash	White willow	Hackberry
Pachypsylla celtidismamma (hackberry nipplegall maker)									L
Pachypsylla celtidisvesicula (hackberry blister gall)									L
Pachypsylla gemma (hackberry bud gall)									B
Pachypsylla venusta (hackberry petiolegall)									L
Pemphigus populicaulis (poplar leaf-petiolegall aphid)						L			
Pemphigus populiramulorum (poplar twiggall aphid)						T			
Pemphigus populitransversus (poplar petiolegall aphid)						L			
Pontania hospes (willow apple gall)								L	
Pontania proxima (bean gall sawfly)								L	
Rhabdophaga strobiloides (pine cone gall)								L	

Polyphemus moth
(Antheraea polyphemus)

Red-humped oakworm
(Symmerista albifrons)

Spring cankerworm
(Paleacrita vernata)

Plate 2

Blackheaded ash sawfly
(Tethida cordigera)

Larch sawfly
(Pristiphora erichsonii)

Pepper-and-salt moth
(Biston cognataria)

Spruce needle miner
(Taniva albolineana)

Two-year-cycle budworm
(Choristoneura biennis)

Pearslug
(Caliroa cerasi)

Plate 4

A twig aphid
(*Pterocomma* sp.)

Chokecherry aphid
(Aphis cerasifoliae)

Fall webworm
(Hyphantria cunea)

Ash borer
(Podosesia syringae fraxini)

Elm sphinx
(Ceratomia amynton)

A dagger moth
(Acronicta dactylina)

Western pine tip moth
(Rhyacionia bushnelli)

Forest tent caterpill
(Malacosoma disstri

Plate 6

Prairie tent caterpillar *(Malacosoma californicum lutescens)*

ooper *(Erannis tiliaria)*

Plate 7

Woolly apple aphid
Eriosoma lanigerum)

Pine pitch-nodule maker
(Petrova luculentana)

Yellownecked caterpillar
(Datana ministra)

Yellowheaded spruce sa
(Pikonema alaskensis)

Plate 8

Carpenterworm *(Prionoxystus robiniae)*

ects feed internally on woody tissue, fruits, seeds, or leaves.

Larvae mine leaves 2
'. Larvae bore into wood or fruit 17

). Feed in hardwood leaves 3
'. Feed in spruce, larch, or tamarack needles 14

). Larvae construct serpentine or linear mines 4
'. Larvae construct blotch mines 7

). Feed in bur oak or elm leaves 5
'. Feed in cottonwood or willow leaves 6

). Serpentine mine on upper leaf surface (fig. 86). Bur oak. Larvae present from August to September. *Agromyza* sp ..... **a serpentine leafminer**
'. Linear mine on upper leaf surface. Mine narrow and terminates in a blotch. American elm, Siberian elm. Larvae present from May to July. *Agromyza aristata* Malloch ..... **a leafmining fly**

ure 86.—*Agromyza* sp. on bur oak.

6(4). Meandering mine on lower leaf surface. Frass arrange in a definite trail (fig. 87). Cottonwood, aspen. Larv present from July to August. *Phyllocnistis populiel* (Chambers) . . . . . **aspen leafmin**

6'. Serpentine mine on upper leaf surface. Willow. Larv present during July. *Agromyza* sp. . . . . **a serpentine leafmin**

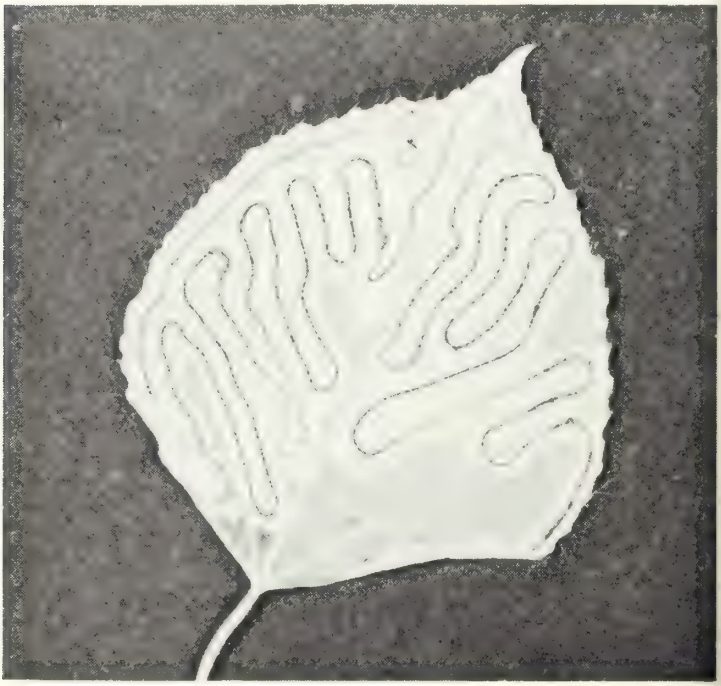


Figure 87.—Damage of aspen leafminer (*Phyllocnistis populiel*

7(3). Head sclerotized . . . . .

7'. Head not sclerotized . . . . .

8(7). Larvae are solitary miners . . . . .

8'. Larvae are gregarious miners. Head and bc depressed, pointed mouthparts. Bur oak. Lar present from June to September. *Cameraria cin natiella* (Chambers) . . . . . **gregarious oak leafmi**

9(8). Head rounded (fig. 89) . . . . .

9'. Head pointed (fig. 90a) . . . . .

0(9). Found on American elm. Mine parallel to leaf vein (fig. 88). Larvae present in June. *Fenusa ulmi* Sundevall
. . . . . **elm leafminer**

10'. Found on cottonwood. Irregular blotch mine on upper leaf surface. Larvae (fig. 89) present from July to August. *Metallus capitalis* (Norton)
. . . . . **a leafmining sawfly**

Figure 88.—Damage of elm leafminer (*Fenusa ulmi*) on American elm. (Photo courtesy Conn. Agr. Exp. Sta.).

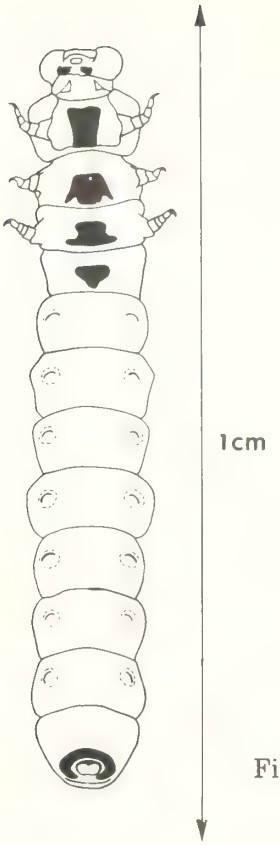


Figure 89.—*Metallus capitalis* (ventral view

11(9). Found on bur oak .....

11'. Found on American elm. Blotch mine. Larvae prese during July. *Cameraria* sp. . . . . **a leafmining caterpil**

12(11). Larvae with prothorax (fig. 7) as wide as metathor head and body depressed, pointed mouthparts (1 90a). Body with dorsally sclerotized plates. Lar feed in irregular blotch mine (fig. 90b). Bur o Larvae present from June to August. *Cameraria har dryadella* (Clemens) . . . . . **.solitary oak leafmi**

12'. Larvae with prothorax wider than metathorax, bo depressed and tapers caudally (fig. 91). Body with dorsally sclerotized plates. Larvae feed in irregu blotch mine. Bur oak. Larvae present during Ju *Brachys aerosus* (Melsheimer) . . **a leafmining bupres**

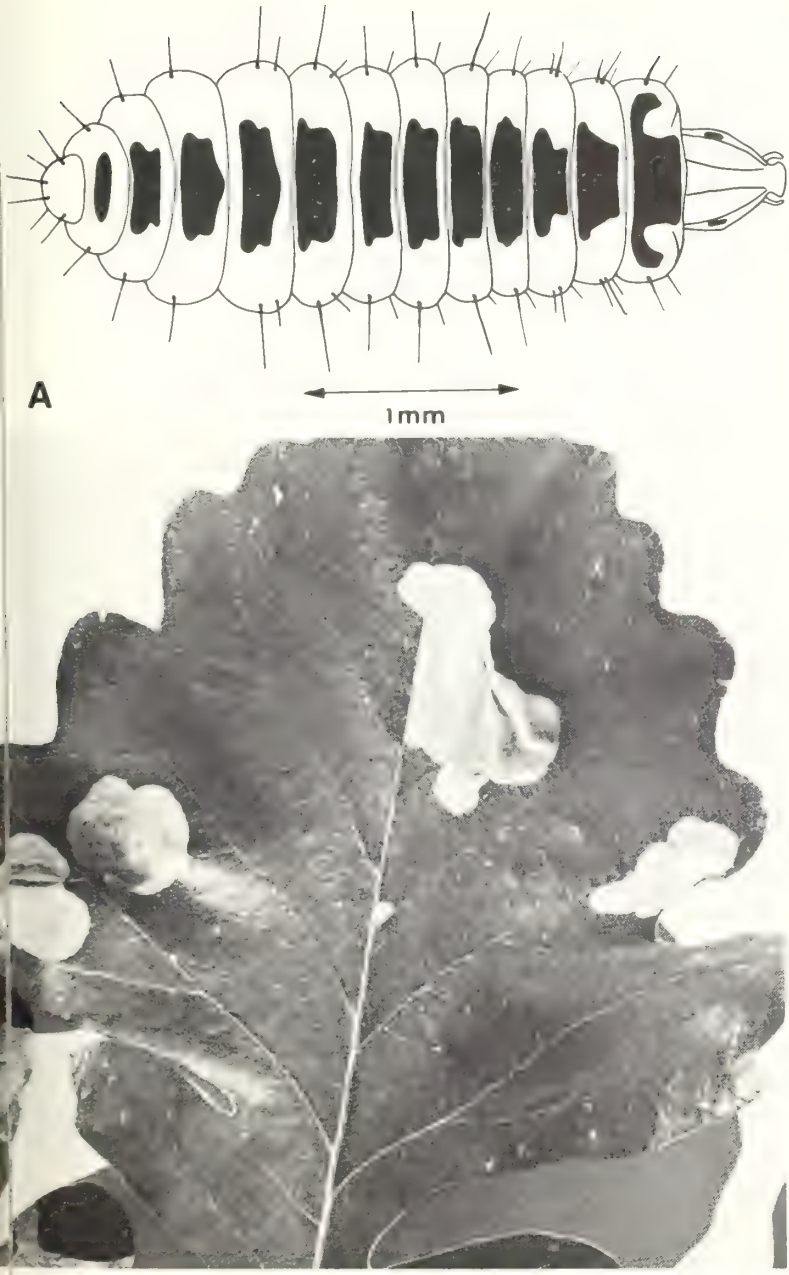


Figure 90.—Solitary oak leafminer (*Cameraria hamadryadella*): A, larva; B, leaf mine on bur oak.

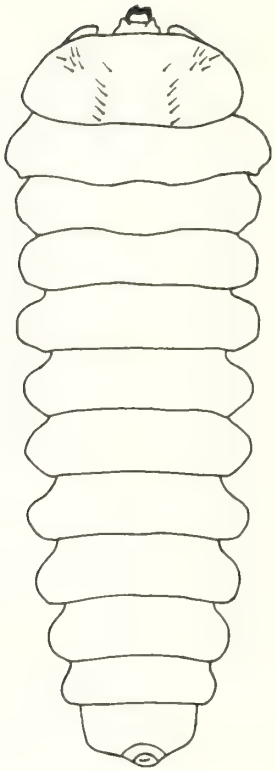


Figure 91.—*Brachys aerosus* (dorsal view).

13(7). Found on bur oak. Larvae feed in blotch mine u
upper leaf surface from June to August. *Japa*
gromyza viridula (Coquillett) . . . . . **a leafmining**
13'. Found on cottonwood. One or more larvae feed
dark irregular blotch mine from July to Aug
Agromyza populoides Spencer . . . . . **a leafmining**

14(2). Spruce needles mined 5
14'. Larch needles mined, late summer and early spr
Larvae live within a case (fig. 92) which is attache
needles while feeding. Siberian larch, tamarack. La
present from July to June. *Coleophora laricella*
(Hübner) . . . . . **larch casebe**

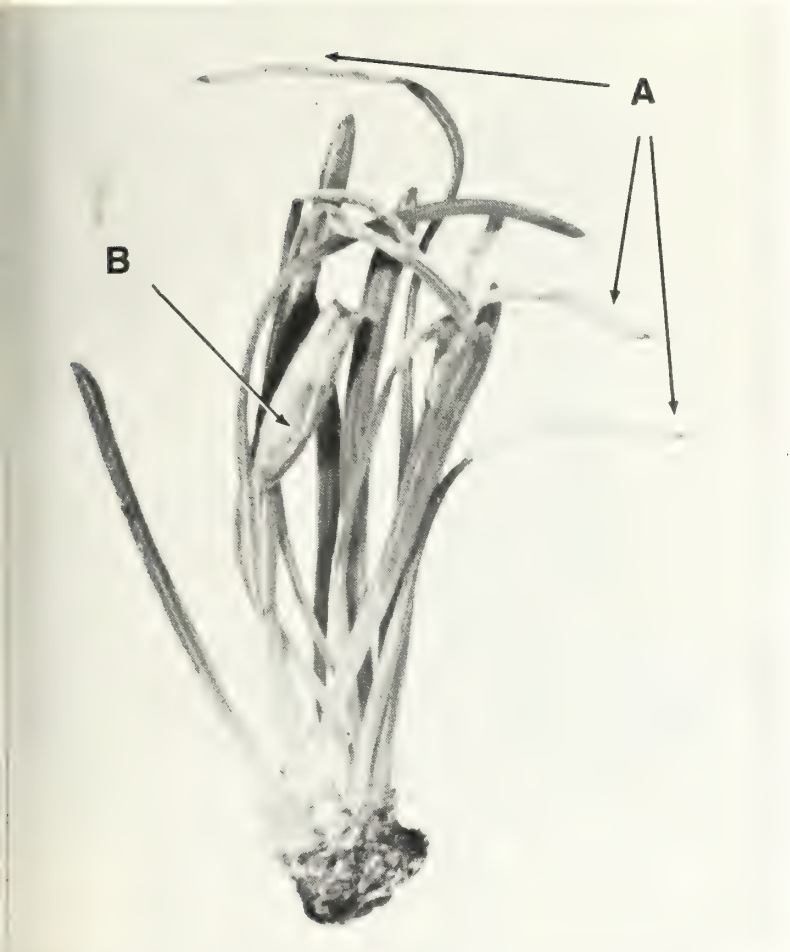


Figure 92.—Larch casebearer (*Coleophora laricella*): A, needle mining damage on Siberian larch; B, needle with case attached.

(14). Frass absent from the mine 16
5'. Frass present in the mine, needles mined from base to apex. Loose webbing containing a silken tube surrounds the needles, accumulation of frass in webbing and tube (fig. 93). White spruce, blue spruce. Adults active from May to June. *Epinotia nanana* (Treitchke) ..... **a needlemining caterpillar**

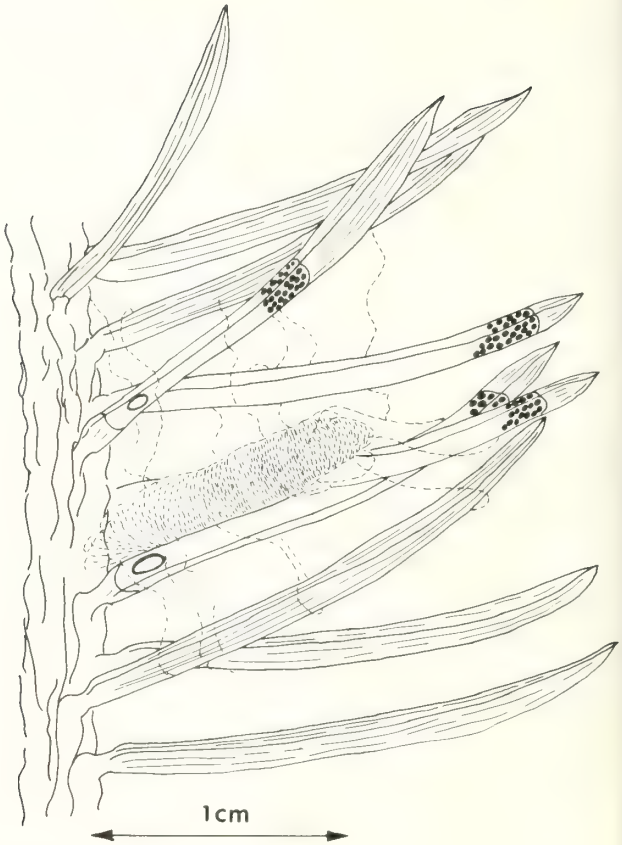


Figure 93.—Damage of *Epinotia nanana*.

16(15). Larvae densely web cut needles together. More th one larvae present, accumulation of frass in webbi (plate 3; fig. 94). Pupate in frass heap. White spru blue spruce. Adults active from June to July. *Tan albolineana* (Kearfott) . . . . . **spruce needle mir**

16'. Larvae loosely web uncut needles (fig. 95). Only o larva present, very little accumulation of frass webbing. White spruce, blue spruce. Adults active fr June to July. *Pulicalvaria piceaella* (Kearfott) . . . . . **a needle mining caterpill**

Figure 94.—Spruce needle miner (*Taniva albolineana*): A, webbed needles; B, needle mine entrance.

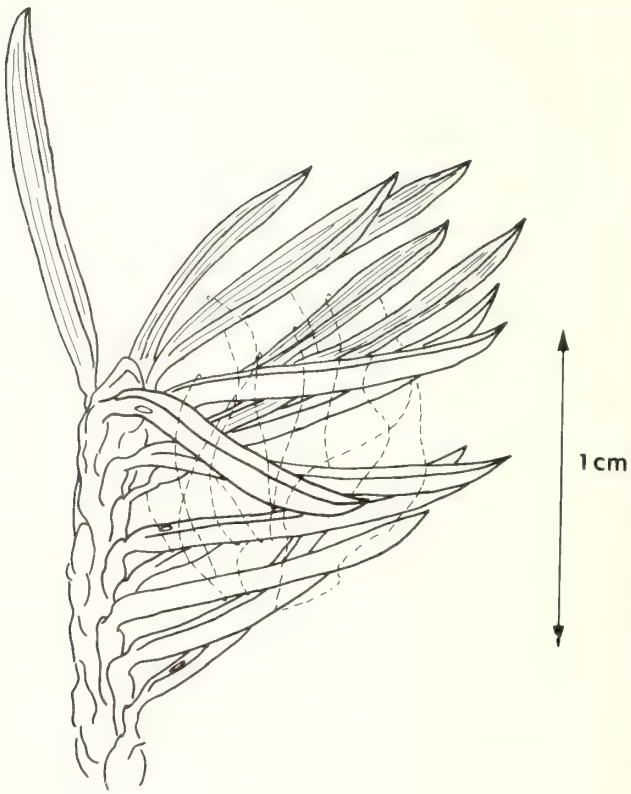


Figure 95.—Damage of *Pulicalvaria piceaella*.

17(1). Larvae feed in seed or in pine cones . . . . . .
17'. Larvae feed on roots, bore under bark or into wood. . . . . .

18(17). Found on hardwood trees . . . . . .
18'. Found on ponderosa pine. Caterpillars mine the brac and seeds of pine cones (fig. 96). One or more larv pupate in the cone. Larvae found from July to Augu
Dioryctria auranticella (Grote) . . . . . a pine cone mo
Dioryctria disclusa Heinrich . . . . . a pine cone mo

ure 96.—Damage of *Dioryctria auranticella* to ponderosa pine cone.

(18). Larvae infest seeds of Siberian peashrub or green ash 20
9'. Larvae infest plums or acorns 21

(19). Found in green ash seeds. Grublike larvae present from July to the following May. *Thysanocnemis* nr. *fraxini* LeConte . . . . . **an ash seed weevil**
0'. Found in Siberian peashrub seeds. Grublike larvae present from July to the following May. (fig. 97). *Bruchophagus caraganae* (Nikolskaya) . . . . . **caragana seed chalcid**

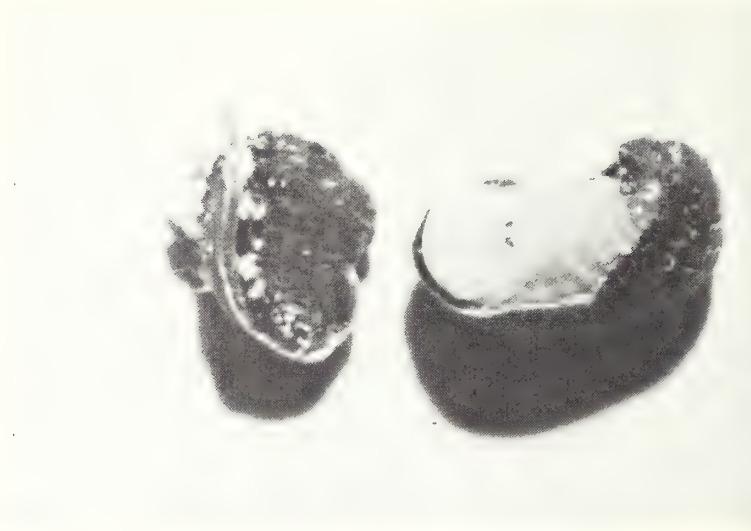


Figure 97.—Caragana seed chalcid (*Bruchophagus caraganae*).

21(19). Grublike larvae in plum fruit .....
21'. Grublike larvae in acorns, pupate in the soil. Bur oa
Larvae present from July to August.
Conotrachelus posticatus Boheman. . . an acorn wee
Curculio strictus (Casey) .....an acorn wee
Curculio iowensis (Casey) .....an acorn wee

22(21). Larvae pupate in the pit. American plum. *Anthonom*
scutellaris LeConte .....plum gou
22'. Larvae pupate in the soil, crescent-shaped egg pu
tures on fruit. American plum. *Conotrache*
nenuphar (Herbst) .....plum curcu

23(17). Found in evergreen trees .....
23'. Found in hardwood trees .....

24(23). Larvae feed on live wood .....
24'. Larvae feed on dead wood .....

25(24). Larvae feed in buds, twigs, or branches .....
25'. Larvae feed on roots. Grublike larva C-shaped (
98c) pupates in the soil (fig. 98a). White spruce, b
spruce. Adults (fig. 19) active during July. *Polyphy*
hammondi LeConte ..... a June bee

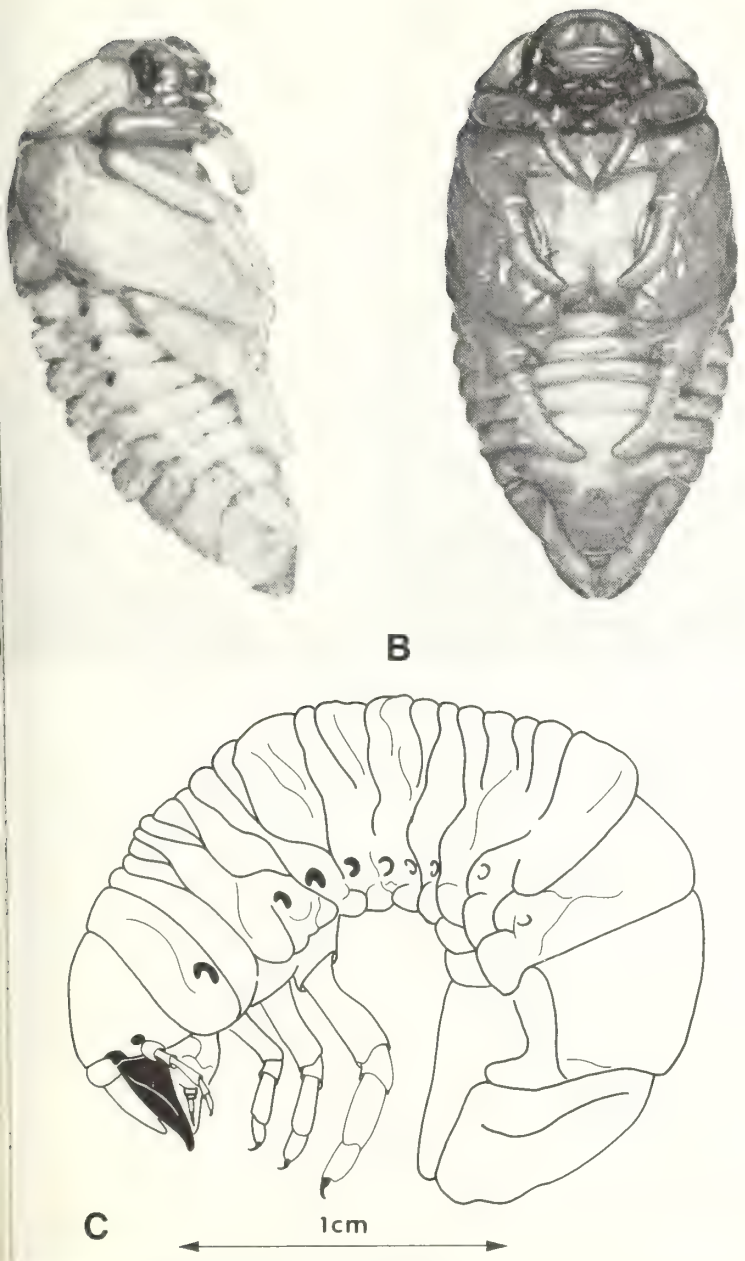


Figure 98.—*Polyphylla hammondi*: A, pupa (lateral view); B, pupa (ventral view); C, larva (lateral view).

26(25). Larvae infest terminal twigs 27
26'. Larvae infest terminal or lateral buds and bore in center of the twig (plate 6; fig. 99). Ponderosa pin Austrian pine, Scotch pine. Larvae present from Ju to August. *Rhyacionia bushnelli* Busck . . . . . **western pine tip mo**

Figure 99.—Needle mining stage of the western pine tip m *(Rhyacionia bushnelli).*

27(26). Pitch nodule on twig or branch 28
27'. Wilted brown terminal (fig. 100), grublike larvae f downward under bark and destroy 2 or more years growth. White spruce, blue spruce. Larvae present fr May to July. *Pissodes strobi* (Peck) . . **white pine we**

ıre 100.—White pine weevil (*Pissodes strobi*): A, dead spruce terminal; B, emergence holes; C, bark removed to expose chip cocoons associated with emergence holes.

28(27). Pitch blister ¼ inch in diameter (plate 7). Ponderos
pine, Scotch pine. Larvae present from June to Augus
Petrova luculentana (Heinrich)
. . . . . **pine pitch-nodule mak**

28'. Pitch mass ½ inch or more in diameter (fig. 101
Austrian pine, Scotch pine, ponderosa pine. Larva
present from June to August. *Dioryctria zimmerma*
(Grote) . . . . . **Zimmerman pine mot**
Dioryctria tumicolella Mutuura & Munroe
. . . . . **a pitch mass bor**

Figure 101.—Pitch mass made by Zimmerman pine moth (*Dior*
tria zimmermani) on ponderosa pine.

9(24). Tunnel less than 3 inches long with numerous side branches (fig. 102) 30

29'. Tunnel more than 3 inches long with no side branches 31

0(29). Adult beetles with toothed elytra (fig. 103a). Radial gallery associated with branch whorl (fig. 102), grublike larvae infest medium to large branches. Ponderosa pine. *Orthotomicus caelatus* Eichhoff . . . . . **a bark beetle**

30'. Adult beetles with rounded elytra (fig. 103b). Radial gallery associated with branch whorl, grublike larvae infest medium to large branches in dying trees. Ponderosa pine. *Pityophthorus* prob. *inquietus* Blackman . . . . . **a bark beetle**

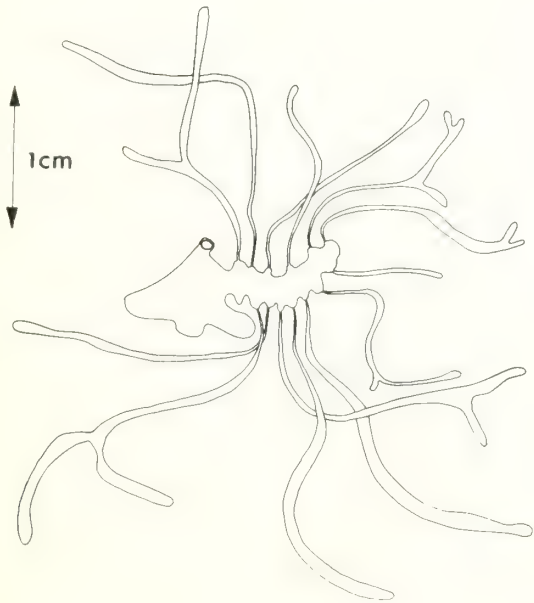


Figure 102.—Gallery of *Orthotomicus caelatus*.

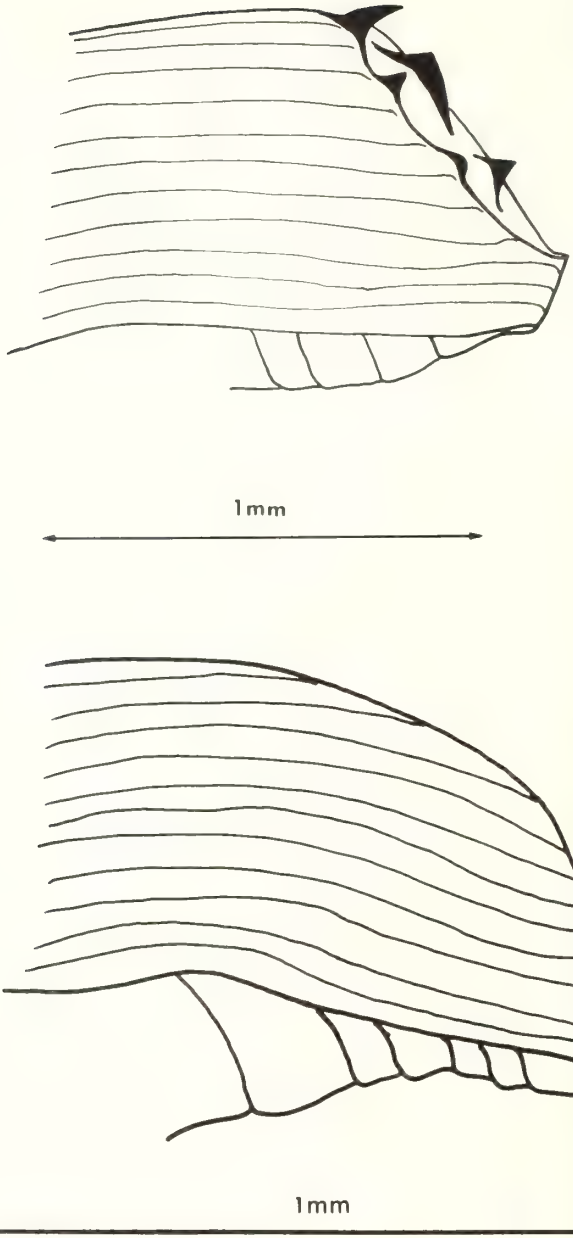


Figure 103.—Examples of elytra: A, *Orthotomicus caelatus*; *Pityophthorus inquietus*.

29). Tunnel with tightly packed, granular frass 32
1'. Tunnel with fibrous frass. Larvae bore under bark of recently killed tree and construct U-shaped pupal chamber in heartwood. Ponderosa pine. *Monochamus maculosus* Haldeman . . . . . **spotted pine sawyer**

31). Larvae feed in limbs 1½ inches or more in diameter 33
2'. Larvae feed in limbs less than 1½ inches in diameter, pupate between two wads of fibrous chips. Ponderosa pine. Adults active from June to August. *Batyle ignicollis ignicollis* (Say) . . . **a roundheaded wood borer** (fig. 104) *Pogonocherus mixtus* Haldeman . . . . . **a roundheaded wood borer**

ure 104.—Adult *Pogonocherus mixtus* (6-7 mm).

33(32). Feeds in pine 3
33'. Feeds in Siberian larch. Larvae bore under bark i trunk and larger branches. *Neoclytus muricatulu muricatulus* (Kirby) .....**a roundheaded wood bore**

34(33). Larvae bore under bark at the base of dead tree Ponderosa pine. *Arhopalus foveicollis* (Haldeman) ..... **a roundheaded wood bor**
34'. Larvae bore under bark in trunk and larger branche Ponderosa pine. (fig. 105) *Neoclytus acuminatus* (F.) ..... **redheaded ash bor**
Neoclytus muricatulus muricatulus (Kirby) ..... **a roundheaded wood bor**
(fig. 104) *Pogonocherus mixtus* Haldeman ..... **a roundheaded wood bor**

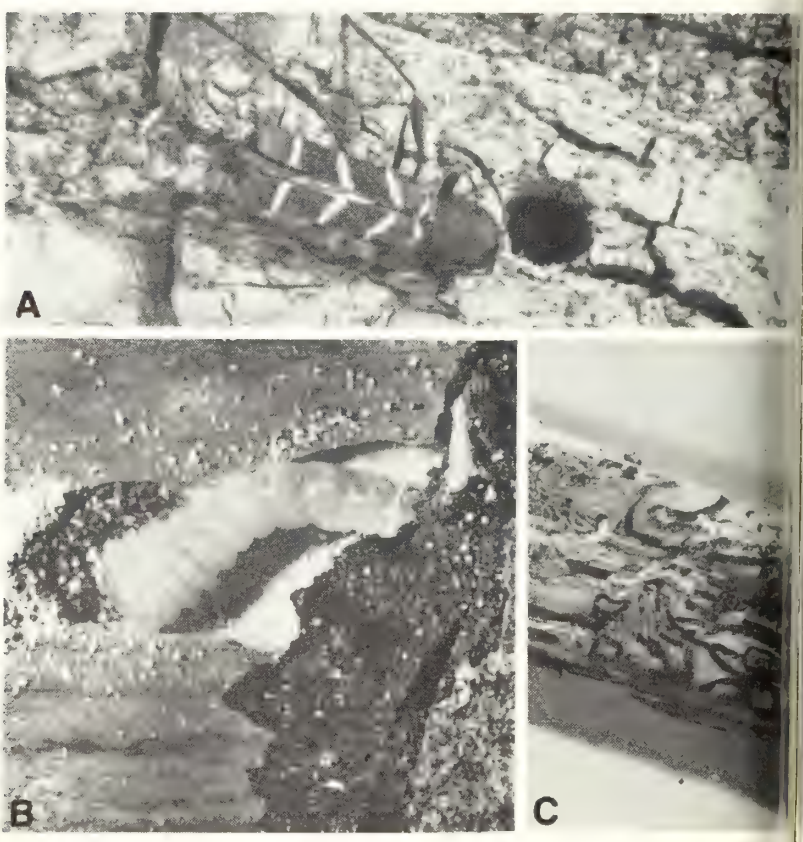


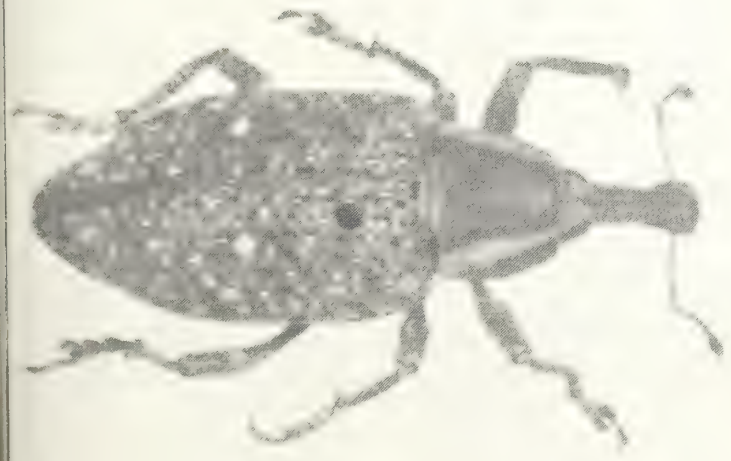
Figure 105.—Redheaded ash borer (*Neoclytus acuminatus*): adult and emergence hole; B, larva; C, tunnels.

(23). Larvae found in live wood 36
35'. Larvae found in dead wood 68

(35). Larvae tunnel under bark 37
36'. Larvae tunnel in heartwood 51

(36). Larvae bore into root collar (in trunk at ground level) 38
37'. Larvae not associated with the root collar 39

(37). Larvae linear, with sclerotized plates on top of all body segments, pupate under bark or in sapwood. Willow and cottonwood stool beds. *Mecas inornata* Say ..... **a roundheaded wood borer**
38'. Larvae C-shaped pupate under bark. Willow stool beds. (fig. 106) *Lepyrus palustris* Scopoli ..... **a weevil**



ıre 106.—An adult *Lepyrus palustris* (12 mm).

39(37). Larvae bore into trunk or main branches 40
39'. Larvae bore into twigs and side branches 46

40(39). Tunnels not associated with bark wounds 41
40'. Tunnels associated with bark wounds. Larvae have dorsal thoracic plate marked with inverted "V," pupate under bark. Two-year life cycle. Cottonwood *Poecilonata cyanipes* (Say) . . . **flatheaded poplar borer**

41(40). Tunnels less than 5 inches in length 42
41'. Tunnels more than 5 inches in length 44

42(41). Tunnel not strongly sinuous 43
42'. Tunnel strongly sinuous (fig. 107), transverse. Unsuccessful attack. Cottonwood. *Agrilus liragus* Barter & Brown . . . . . **bronze poplar borer**

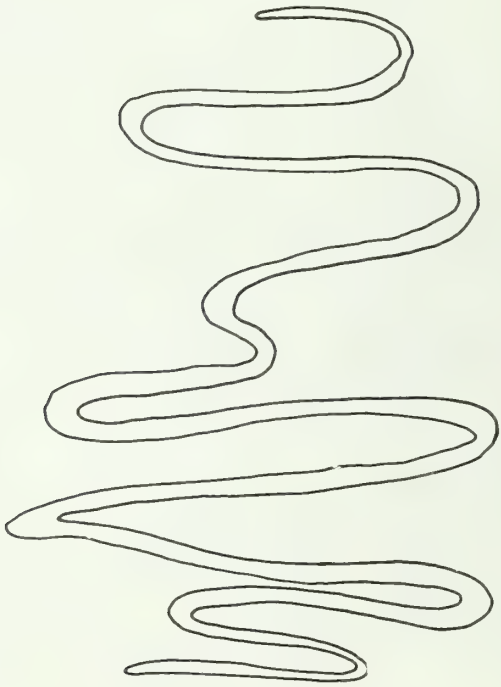


Figure 107.—Gallery of unsuccessful attack of bronze poplar borer (*Agrilus liragus*).

3(42). Tunnels radiating from the same point (fig. 108b), unstained, larvae C-shaped (fig. 108a) and pupate under bark. American elm, Siberian elm.
Magdalis armicollis (Say) . . . . . **red elm bark weevil**
Magdalis barbita (Say) . . . . . **black elm bark weevil**

43'. Tunnels parallel to the grain (fig. 109) and originating from a transverse egg gallery. Yellowish foliage in July and August. Green ash. *Leperisinus californicus* Swaine . . . . . **a bark beetle**
(fig. 110) *Leperisinus aculeatus* Say
. . . . . **eastern ash bark beetle**

Figure 108.—Bark removed to expose larva of the red elm bark weevil (*Magdalis armicollis*).

44(41). Fifth larval body segment longer than wide, spine present on last abdominal segment (fig. 111) 4

44'. Fifth larval body segment wider than long, spine absent on last abdominal segment (fig. 105b). Gree ash. *Neoclytus acuminatus* (F.) . . **redheaded ash bore**

45(44). Found in bur oak. Pupate under bark or in sapwood Adults active from June to July. *Agrilus obsolet guttatus* Gory . . . . . .**a flatheaded wood bore**

45'. Found in cottonwood. Pupate under bark or i sapwood (fig. 107). Adults active from June to July *Agrilus liragus* Barter & Brown . . . **bronze poplar bore**

46(39). Tunnel in branches more than 1½ inches in diameter 4

46'. Tunnel in branches less than 1½ inches in diameter .4

47(46). Main tunnel meanders under the bark 4

47'. Main tunnel transverse (egg gallery), stained. Larv tunnels parallel the grain. Yellowish foliage in July a August. Green ash. (fig. 109).
Leperisinus californicus Swaine . . . . . .**a bark beet**
(fig. 110) *Leperisinus aculeatus* Say
. . . . . **eastern ash bark beet**

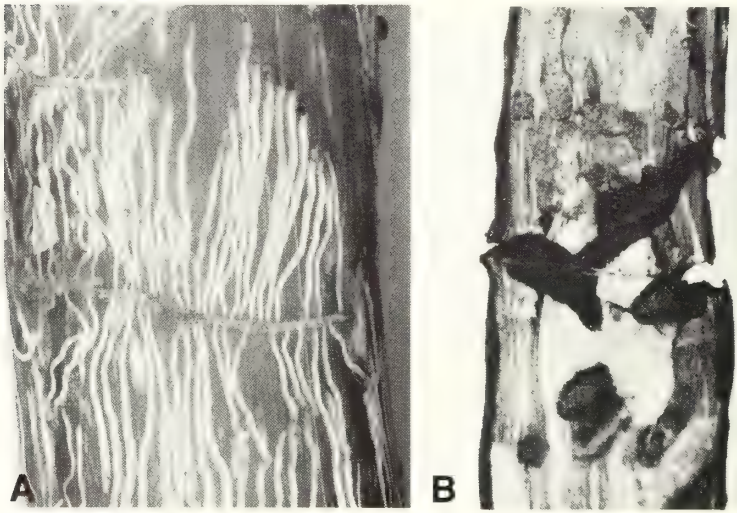
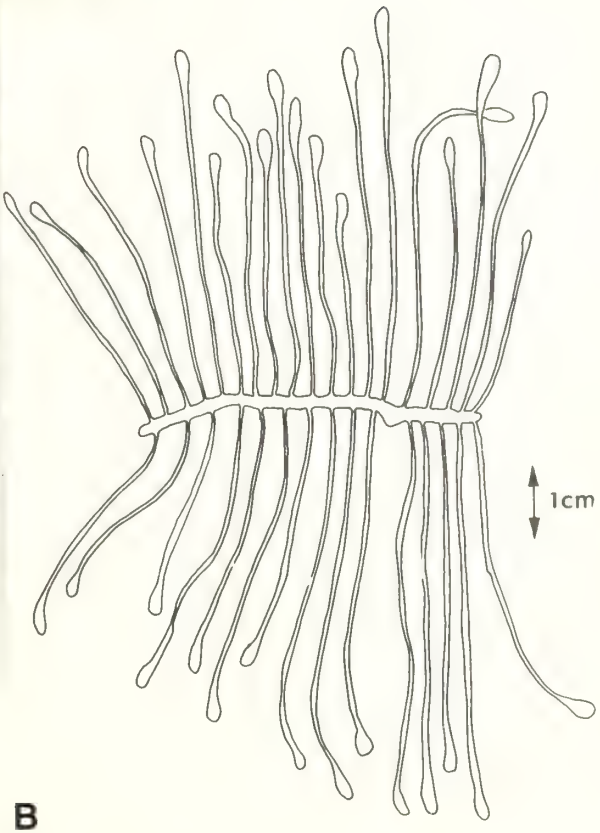


Figure 109.—*Leperisinus californicus*: A, gallery in large bran B, gallery girdling small branch (note characteris stain of *Ceratocystis* fungus).



B

Figure 110.—Galleries of the eastern ash bark beetle (*Leperisinus aculeatus*): A, galleries in small branch; B, generalized drawing.

48(47). Fifth larval body segment longer than wide, spine present on last abdominal segment (fig. 111). Bur oak Adults active from June to July. *Agrilus obsoleto guttatus* Gory . . . . . .**a flatheaded wood bore**

48'. Fifth larval body segment wider than long, spine absent on last abdominal segment (fig. 105b) American elm, Siberian elm, green ash. Adults activ from June to August. *Neoclytus acuminatus* (F.) . . . . . **redheaded ash bore**

49(46). Main tunnel meanders under the bark 5

49'. Main tunnel transverse (egg gallery), stained. Larva tunnels parallel the grain. Yellowish foliage in July an August. Green ash. (fig. 109) *Leperisinus californicu* Swaine . . . . . **a bark beetl**

(fig. 110) *Leperisinus aculeatus* Say . . . . . **eastern ash bark beet**

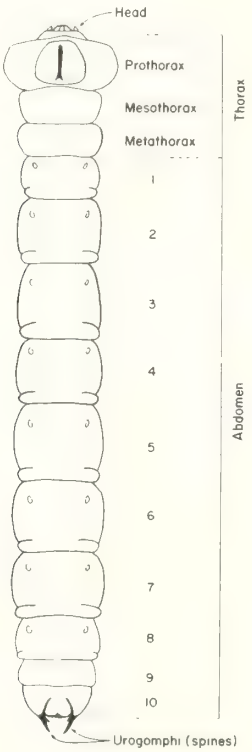


Figure 111.—Generalized drawing of an *Agrilus* larva.

)(49). Larvae with 5th body segment longer than wide, spines present on last abdominal segment (fig. 111). Meandering or zigzag mine alternates between bark and sapwood. Bur oak. Adults present from May to July. *Agrilus bilineatus* (Weber) . . . **twolined chestnut borer**

50'. Larvae with 5th body segment wider than long, spines absent on last abdominal segment. Meandering mines at base of twigs. Willow and cottonwood stool beds. Adults active during July. *Mecas inornata* Say . . . . . **a roundheaded wood borer**

(36). Bores into root collar or roots 52

51'. Bores into wood more than 6 inches aboveground . .57

2(51). Found in roots 53

52'. Found in root collar 54

3(52). Found in cottonwood stool beds. Tunnel ¼ inch in diameter. Head light to dark brown, abdominal prolegs (fig. 7) present. *Aegeria tibialis* (Harris) . . . . . **a clearwinged moth**

53'. Found in bur oak. Tunnel ½ inch in diameter. Head black, abdominal prolegs absent. Adults (fig. 112) present from July to August. *Prionus imbricornis* (L.) . . . . . **tilehorned prionus**

gure 112.—Tilehorned prionus (*Prionus imbricornis*).

54(52). Larvae infest willow or cottonwood i

54'. Larvae infest green ash, tunnel ¼ inch or less i diameter (plate 5; fig. 113). Larva white with lig brown head. Two-year life cycle. Adults present frc May to September. *Podosesia syringae fraxini* Lugger . . . . . ash bor

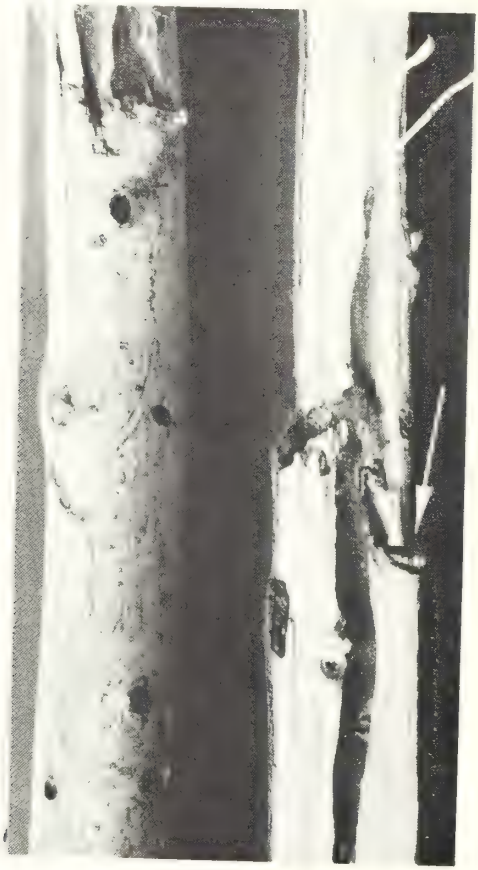


Figure 113.—Damage of the ash borer (*Podosesia syringae fra ini*) in green ash. Note cast pupal skin.

55(54). Larvae linearly narrow 5

55'. Larvae C-shaped, similar to figure 108a, tunnel und bark and in sapwood, construct pupal chamber upwar in the heartwood. Willow and cottonwood stool bed Adults (fig. 16) active from July to Septembe *Cryptorhynchus lapathi* (L.). . poplar-and-willow bor

6(55). Tunnels ¼ inch or less in diameter. Head round and visible, abdominal prolegs (fig. 7) present (caterpillar). Cottonwood stool beds. *Aegeria tibialis* (Harris) . . . . . **a clearwinged moth**

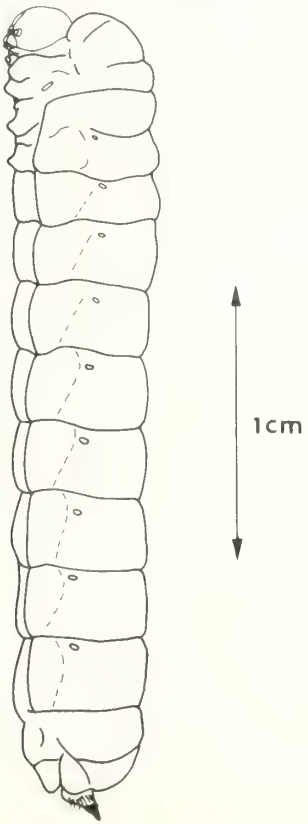
56'. Tunnels ½ inch in diameter. Head depressed and retracted, abdominal prolegs absent. Willow and cottonwood stool beds. *Plectrodera scalator* (F.) . . . . . **cottonwood borer**

7(51). Larvae bore into trunk and large branches 58

57'. Larvae bore into twigs and small branches 65

8(57). Larvae infest willow, green ash, American elm, Siberian elm 59

58'. Larvae infest boxelder, cottonwood 62



igure 114.—Pigeon tremex (*Tremex columba*).

59(58). Tunnel packed with granular frass 6
59'. Tunnel without frass 6

60(59). Tunnel round in cross section. Larva with spine on er
of abdomen (fig. 114). American elm, Siberian elr
Tremex columba (L.) . . . . . **pigeon treme**
60'. Tunnel elliptical in cross section. Larva without spi
on end of abdomen, dorsal thoracic plate marked wi
an inverted "V" (fig. 115). Green ash. *Dicerca diva*
cata (Say) . . . . . .**a flatheaded wood bor**

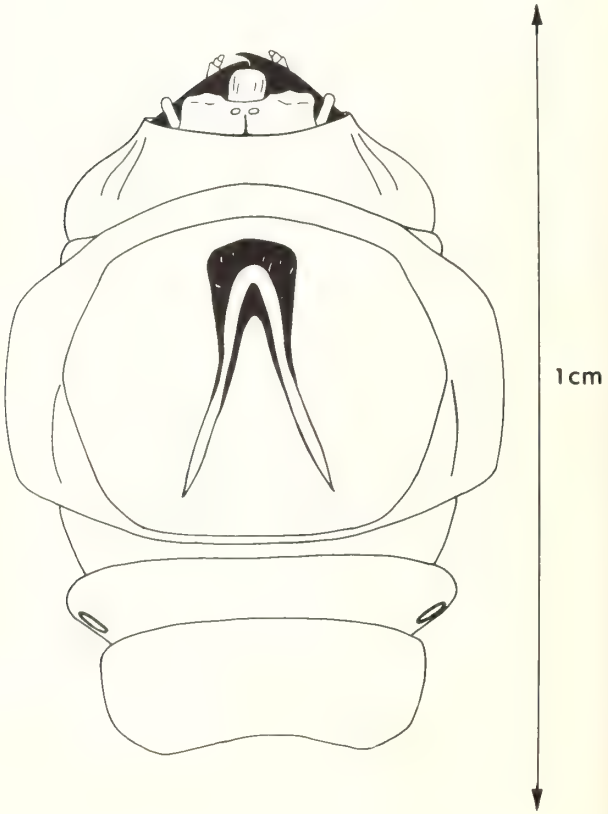


Figure 115.—Larva of *Dicerca divaricata*.

59). Tunnel ¼ inch or less in diameter (fig. 113). Larva white with light brown head (plate 5). Two-year life cycle. Green ash. Adults present from May to September. *Podosesia syringae fraxini* Lugger ..... **ash borer**

1'. Tunnel ½ inch or less in diameter (fig. 116). Larva light green to reddish white (plate 8) with dark brown head. Three-year life cycle. Willow, green ash, American elm, Siberian elm. Adults present from June to July. *Prionoxystus robiniae* (Peck) ..... **carpenterworm**

ure 116.—Multiple attacks on green ash by the carpenterworm (*Prionoxystus robiniae*). Note empty pupa cases.

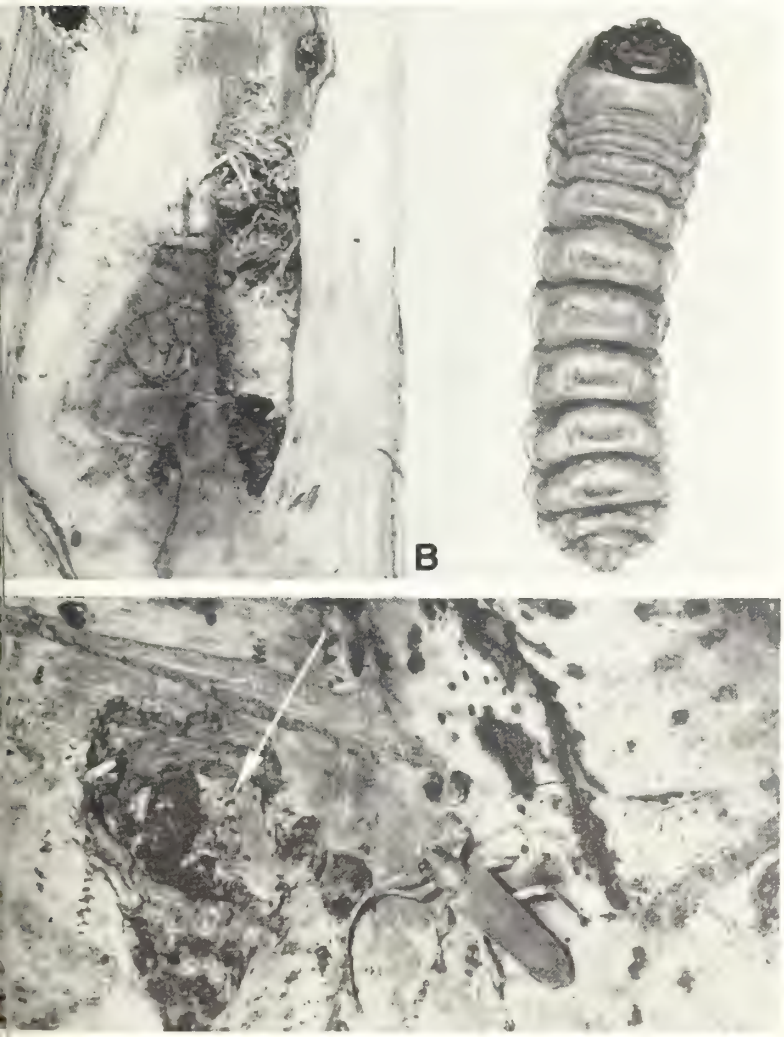
62(58). Tunnel packed with granular frass ..... (
62'. Tunnel without frass ..... (

63(62). Tunnel round in cross section. Larva with spine on er
of abdomen (fig. 114). Boxelder, American el
Siberian elm. *Tremex columba* (L.) ... **pigeon treme**
63'. Tunnel elliptical in cross section. Larva without spi
on end of abdomen, dorsal thoracic plate marked wi
an inverted "V" (fig. 115). Boxelder, cottonwood. (fi
117a) *Dicerca divaricata* (Say)
..... **a flatheaded wood bor**
(fig. 117b) *Dicerca tenebrica* (Kirby)
..... **a flatheaded wood bor**

Figure 117.—*Dicerca* spp.: A, *Dicerca divaricata* (note diverg
wing tips); B, *Dicerca tenebrica*.

(62). Larva with brown retracted head, body white, abdominal prolegs absent (fig. 118). Cottonwood. *Saperda calcarata* Say . . . . . **poplar borer**

64'. Larva with dark brown visible head, body light to reddish white (plate 8), abdominal prolegs present. Boxelder, cottonwood. *Prionoxystus robiniae* (Peck) . . . . . **carpenterworm**



ıre 118.—Poplar borer (*Saperda calcarata*): A, pupal cell with frass plug; B, larva (ventral view); C, adult with bark depression indicating an attack.

65(57). Larvae infest willow, cottonwood .....(
65'. Larvae infest bur oak, boxelder, hackberry, green ash
..... (

66(65). Larvae C-shaped, similar to figure 108a. Bore und
bark and in sapwood, construct pupal chamber upwa
in heartwood. Willow, cottonwood. Adults (fig. 1
present from July to September. *Cryptorhynchus*
lapathi (L.)..... **poplar-and-willow bor**
66'. Larvae S-shaped (fig. 119). Bores down pith of tw
pupates in pith. Willow stool bed. Adults present fro
May to June. *Janus abbreviatus* (Say)
....**willow shoot sawf**

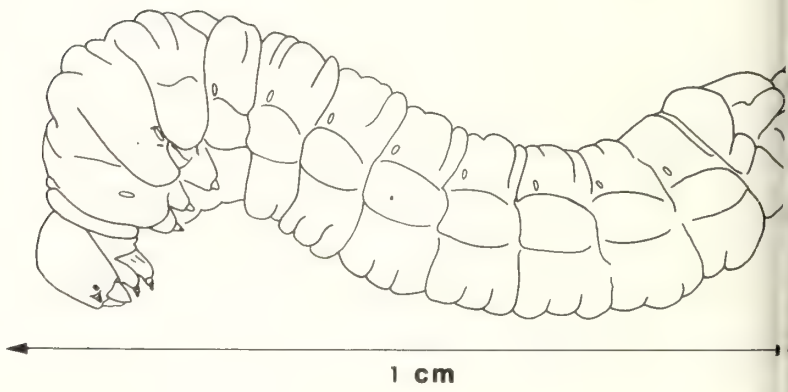
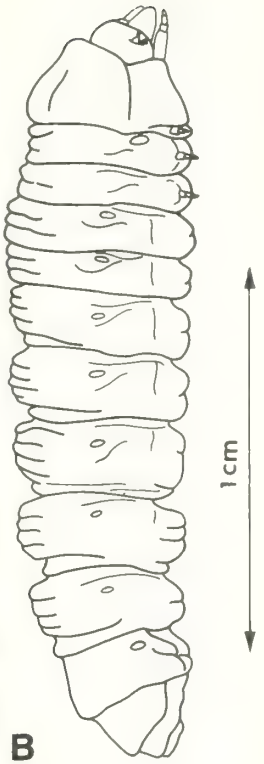


Figure 119.—Willow shoot sawfly (*Janus abbreviatus*).

67(65). Larvae prune twig and pupate in portion attached
tree. Larva white with retracted head, tunnel in t
pith. Bur oak, green ash. Adults present from June
August. *Psyrassa unicolor* (Randall) .... **a twig pru**
67'. Larvae prune twig and pupate in severed twig betw
two fibrous wads. Larva white with retracted h
(fig. 120), tunnel in twig pith. Bur oak, boxelder, gr
ash, hackberry. Adults present from June to J
Elaphidionoides villosus (F.) .....**twig pru**



ure 120.—Twig pruner (*Elaphidionoides villosus*): A, dorsal view of larva with pruned oak twig; B, lateral view of larva.

(35). Wood in state of decay, bark absent 69
8'. Dry wood, bark intact 71

(68). Larvae with depressed body, head retracted 70
9'. Larvae with cylindrical white body, head visible (fig. 114), end of abdomen with brown spine. Tunnel in heartwood. Boxelder, American elm, Siberian elm. Larvae present from June to following May. *Tremex columba* (L.) ..... **pigeon tremex**

70(69). Larvae with dorsal thoracic plate marked with inverte
"V." Tunnel under bark. Cottonwood. *Poecilona*
cyanipes (Say) . . . . . **flatheaded poplar bor**

70'. Larvae with dorsal thoracic plate unmarked. Tunnel
sapwood. Willow. *Saperda mutica* Say
. . . . . **a roundheaded wood bor**

71(68). Larvae C-shaped, cylindrical, short . . . . . .
71'. Larvae linear, depressed, long . . . . . .

72(71). Infest dead or dying elm . . . . . .
72'. Infest dead ash twigs. Transverse unstained gallery,
inch larval mines parallel to wood grain, numero
attacks on the same tree. Green ash. (fig. 12
Leperisinus fasciatus LeConte
. . . . . **whitebanded ash bark bee**
(fig. 122) *Leperisinus criddlei* Swaine
. . . . . **an ash bark bee**

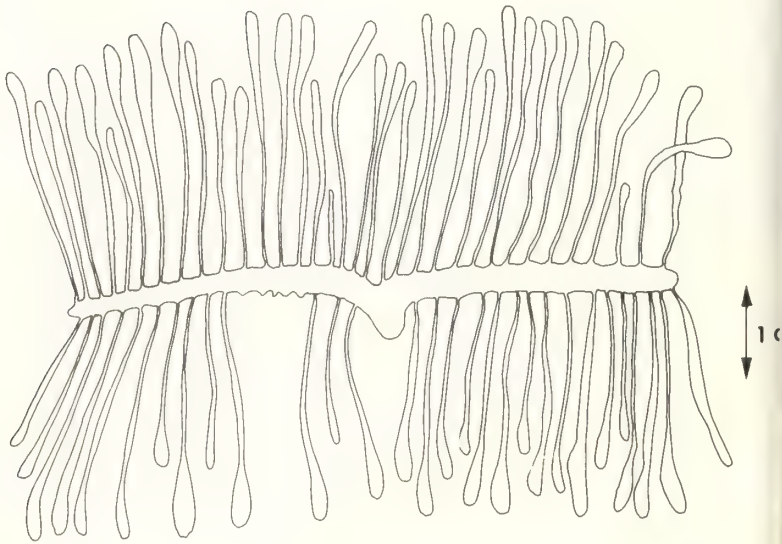


Figure 121.—Gallery of whitebanded ash bark beetle (*Leperis*
fasciatus).

ure 122.—Galleries of *Leperisinus criddlei*.

72). Main gallery transverse, larvae mine parallel to grain, fan-shaped pattern (fig. 123). American elm. *Hylurgopinus rufipes* (Erichhoff) . . . **native elm bark beetle**

3'. Main gallery parallel to grain, transverse larval mines, fan-shaped pattern (fig. 124). American elm. *Scolytus multistriatus* (Marsham)

. . . . . **smaller European elm bark beetle**

Figure 123.—Native elm bark beetle (*Hylurgopinus rufipes*): A, adult; B, egg gallery and larval mines.

ıre 124.—Smaller European elm bark beetle (*Scolytus multistriatus*): A, adult; B, brood galleries on American elm made by female beetles and larvae.

171). Larvae tunnel in center of twig 75
1. Larvae tunnel under bark 76

75(74). Larvae pupate between two wads of fibrous chips ; center of twig. Bur oak. Adults present from May t August. *Batyle saturalis saturalis* (Say) . . . . . **a roundheaded wood bor**

75'. Larvae pupate using only one fibrous wad, excava emergence hole before pupation. Bur oak, boxelde hackberry. Adults present from May to July. *Elapi dion mucronatum* (Say) . . . . . **spined bark bor**

76(74). Larvae infest bur oak, boxelder, hackberry . . . . . .'

76'. Larvae infest cottonwood, green ash, American el Siberian elm . . . . . .

77(76). Dorsal thoracic plate marked (fig. 125) . . . . . .'

77'. Dorsal thoracic plate unmarked . . . . . .

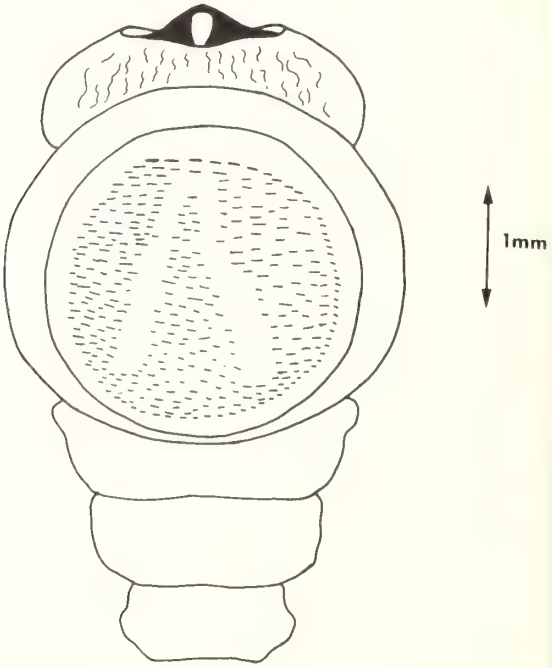


Figure 125.—*Chrysobothris sexsignata* (dorsal view).

3(77). Dorsal thoracic plate with median bisecting line (fig. 111), last abdominal segment with spines (fig. 126) 79

78'. Dorsal thoracic plate marked with inverted "V" (fig. 125), last abdominal segment without spines. Bur oak, boxelder. *Chrysobothris sexsignata* (Say) . . . . . **a flatheaded wood borer**

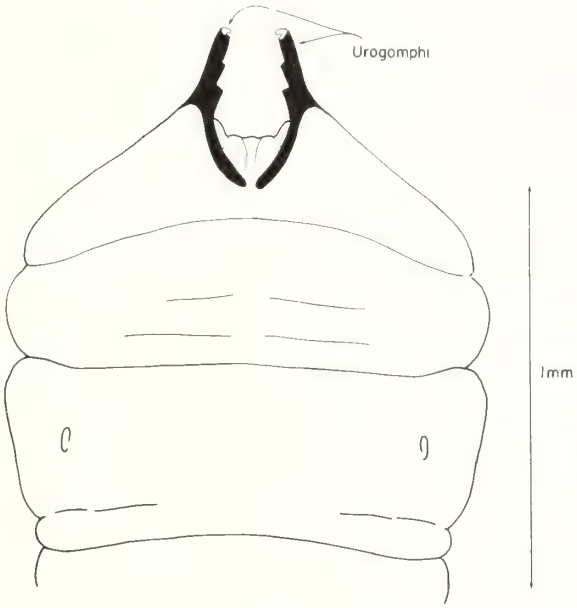


Figure 126.—Dorsal view of last abdominal segments showing spines (*Agrilus* spp.).

')(78). Infest boxelder. Meandering galleries just scoring wood surface (fig. 127). *Agrilus masculinus* LeConte . . . . . **a flatheaded wood borer**

79'. Infest hackberry. Meandering galleries just scoring wood surface.
Agrilus celti Knull . . . . . .**a flatheaded wood borer**
Agrilus lecontei Saunders . . . **a flatheaded wood borer.**

Figure 127.—Bark removed to show damage of *Agrilus mas(* *linus* on dead boxelder (note "D" shaped emerger holes).

80(77). Larvae mine under bark of dead dry twigs, constru pupal chamber under bark or in sapwood. Boxeld *Hyperplatys aspersus* (Say) . . . . . **.a roundheaded wood bo** *Hyperplatys maculatus* Haldeman . . . . . **a roundheaded wood bo**

80'. Larvae mine under bark of live twig the first ye construct long pupal chamber down center of twig t second year. Bur oak, boxelder, hackberry. Adu present from May to July. *Elaphidion mucronatum* (Say) . . . . . **.spined bark bo**

76). Tunnels with tightly packed granular frass 82
1'. Tunnels with fibrous frass. Larvae score bark more than wood, pupate in bark or sapwood. American elm, Siberian elm. *Saperda tridentata* Olivier
. . . . . **elm borer**

81). Dorsal thoracic plate marked (fig. 125) 83
2'. Dorsal thoracic plate unmarked 84

82). Dorsal plate marked with a single bisecting line (fig. 111), last abdominal segment with spines (fig. 126). Larvae tunnel under bark, pupate in sapwood. Green ash. *Agrilus* sp . . . . . **.a flatheaded wood borer**
3'. Dorsal plate marked with inverted "V" (fig.125), last abdominal segment without spines. American elm, Siberian elm, green ash. *Chrysobothris sexsignata* (Say)
. . . . . **a flatheaded wood borer**

82). Larvae infest cottonwood. Meandering tunnels under bark just score the wood, pupate under bark or in sapwood. *Hyperplatys aspersus* (Say)
. . . . . **.a roundheaded wood borer**
Hyperplatys maculatus Haldeman
. . . . . **.a roundheaded wood borer**
4'. Larvae infest green ash. Meandering tunnels under bark generally parallel the wood grain (fig. 105), pupate within inch of wood surface.
Neoclytus acuminatus (F.) . . . . . **redheaded ash borer**
Obrium ruffulum Gahan . . **.a roundheaded wood borer**

WOOD BORERS, BY POINT OF ATTACK

B = branches, C = root collar, K = trunk, P = twig pruner, R = roots, T = twigs

Insect	American elm	Blue spruce	Boxelder	Bur oak	Cotton-wood	Green ash	Hackberry	Ponderosa pine	Siberian elm	Siberian peashrub	White willow
FOUND UNDER BARK OF LIVE TREES											
Agrilus bilineatus (twolined chestnut borer)				T							
Agrilus liragus (bronze poplar borer)					K						
Agrilus obsoletoguttatus (a flatheaded wood borer)				K, B							
Dicerca divaricata (a flatheaded wood borer)			K, B		K, B	K, B					
Dicerca tenebrica (a flatheaded wood borer)					K						
Leperisinus aculeatus (eastern ash bark beetle)						K, B					
Leperisinus californicus (a bark beetle)						K, B					
Lepyrus palustris (a weevil)											C
Magdalis armicollis (red elm bark weevil)	K								K		

B = branches, C = root collar, K = trunk, P = twig pruner, R = roots, T = twigs

Insect	American elm	Blue spruce	Boxelder	Bur oak	Cotton-wood	Green ash	Hackberry	Ponderosa pine	Siberian elm	Siberian peashrub	White willow
FOUND UNDER BARK OF LIVE TREES											
Mecas inornata (a roundheaded wood borer)					T, C				T, C		
Neoclytus acuminatus (redheaded ash borer)	K, B					K, B			K, B		
Pissodes strobi (white pine weevil)		B									
Poecilonata cyanipes (flatheaded poplar borer)					K, B						
FOUND IN HEARTWOOD OF LIVE TREES											
Aegeria tibialis (a clearwinged moth)					C, R						
Cryptorhynchus lapathi (poplar-and-willow borer)					K, C						K, C
Dicerca dwaricata (a flatheaded wood borer)	K, B		K, B		K, B						
Dicerca tenebrica (a flatheaded wood borer)			K, B		K, B						
Eluphidionoides villosus (twig pruner)	P		P	P		P	P				

WOOD BORERS, BY POINT OF ATTACK

B = branches, C = root collar, K = trunk, P = twig pruner, R = roots, T = twigs

Insect	American elm	Blue spruce	Boxelder	Bur oak	Cotton-wood	Green ash	Hackberry	Ponderosa pine	Siberian elm	Siberian peashrub	White willow
FOUND IN HEARTWOOD OF LIVE TREES											
Janus abbreviatus (willow shoot sawfly)											T
Neoclytus acuminatus (redheaded ash borer)	T, B					T, B					
Petrova luculentana (pine pitch-nodule maker)								T			
Podosesia syringae fraxini (ash borer)						K, B					
Prionoxystus robiniae (carpenterworm)			K		K	K			K		K
Prionus imbricornis (tilehorned prionus)				R							
Proteoteras willingana (boxelder twig borer)			T								
Rhyacionia bushnelli (western pine tip moth)								T			
Saperda calcarata (poplar borer)					K, B						

Insect	American elm	Blue spruce	Boxelder	Bur oak	Cotton-wood	Green ash	Hackberry	Ponderosa pine	Siberian elm	Siberian peashrub	White willow
FOUND IN DEAD AND DYING TREES											
Agrilus celti (a flatheaded wood borer)							B				
Agrilus leconteı (a flatheaded wood borer)							B				
Agrilus masculinus (a flatheaded wood borer)			K, B								
Batyle saturalis saturalis (a roundheaded wood borer)				T							
Chrysobothris sexsignata (a flatheaded wood borer)	B		B	B		B			B		
Elaphidion mucronatum (spined bark borer)			P	P			P				
Hylurgopinus rufipes (native elm bark beetle)	K, B										
Hyperplatys aspersus (a roundheaded wood borer)			T, B		T, B						
Hyperplatys maculatus (a roundheaded wood borer)			T, B		T, B						
Lepersinus criddlei (an ash bark beetle)						K, B					

WOOD BORERS, BY POINT OF ATTACK

B = branches, C = root collar, K = trunk, P = twig pruner, R = roots, T = twigs

Insect	American elm	Blue spruce	Boxelder	Bur oak	Cotton-wood	Green ash	Hackberry	Ponderosa pine	Siberian elm	Siberian peashrub	White willow
FOUND IN DEAD AND DYING TREES											
Leperisinus fasciatus (whitebanded ash bark beetle)						K, B					
Neoclytus acuminatus (redheaded ash borer)	K, B					K, B					
Obrium ruffulum (a roundheaded wood borer)						B					
Poecilonata cyanipes (flatheaded poplar borer)					K						
Saperda mutica (a roundheaded wood borer)											K
Saperda tridentata (elm borer)	K, B								K, B		
Scolytus multistriatus (smaller European elm bark beetle)	K, B										
Tremex columba (pigeon tremex)	K		K						K		

Insects feeding on plant sap produce puncture wounds, stippled discoloration, or leaf curls; scale insects.

1. Insects are covered with shell or pitch mass, immobile 2
1'. Insects are free feeding or found within a leaf curl, mobile 7

2(1). Found on evergreens 3
2'. Found on hardwoods 5

3(2). Soft-bodied insect covered with a shell (scale) 4
3'. Maggot covered with pitch mass. Ponderosa pine, blue spruce. *Cecidomyia reeksi* Vockeroth . . . **a pitch midge**

4(3). Scale white with brown cap (fig. 128). Ponderosa pine, Scotch pine, white spruce, blue spruce. Summer. *Phenacaspis pinifoliae* (Fitch) . . . . . **.pine needle scale**
4'. Scale brown, round, deeply concave. White spruce, blue spruce. Summer. *Toumeyella* sp. . **a tortoise scale**

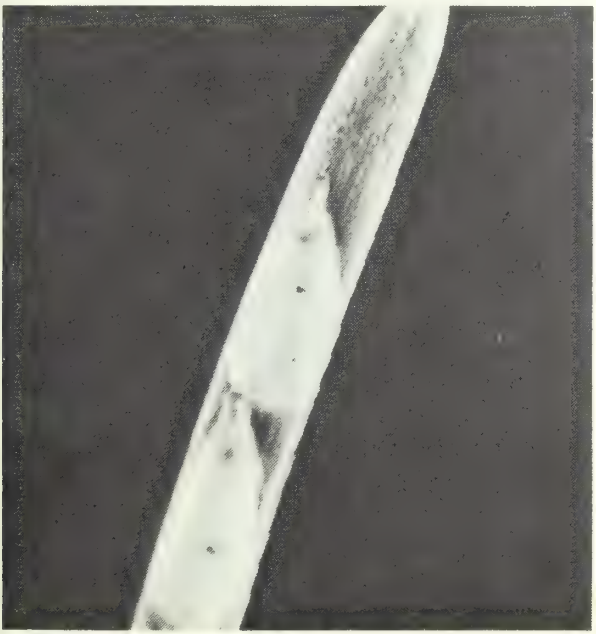


Figure 128.—Pine needle scale (*Phenacaspis pinifoliae*) on spruce.

5(2). Absence of marginal secretion around edge of scale

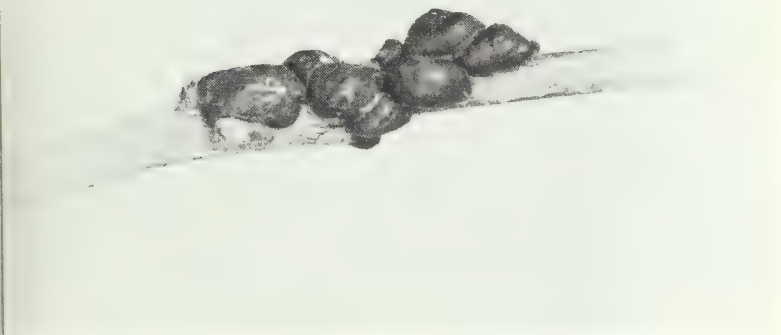
. . . . . .

5'. Presence of flocculent material around edge of sca (fig. 129), ¼ inch in diameter. Green ash, boxelde silver maple. Summer. *Pulvinaria innumerabilis* (Rathvon) . . . . . **cottony maple sca**

Figure 129.—Cottony maple scale (*Pulvinaria innumerabilis*).

). Scale gray to dark brown, dark central nipple; 1/16 inch in diameter. Cottonwood, green ash, boxelder, hackberry. *Aspidiotus ancylus* (Putnam) ..... **Putnam scale**

'. Scale brown (fig. 130), 3/16 inch in diameter. Green ash, boxelder, American elm, Siberian elm. Summer. *Lecanium corni* Bouche .... **European fruit lecanium**



re 130.—European fruit lecanium (*Lecanium corni*) on green ash.

. Found on evergreens 8
. Found on hardwoods 9

. Found on white spruce or blue spruce. Trace of webbing between discolored needles. Mite barely visible to naked eye. *Tetranychus urticae* Koch ..... **twospotted spider mite**

Found on ponderosa pine and Scotch pine. No webbing associated with discolored needles. Aphids with cornicle (fig. 134), body dark brown to black. Aphids present from July to August. *Cinara* sp. . . **a pine aphid**

. Adults with wings, rest flat on back. (fig. 131, 133), hind wings approximately same size as front wings 10

. Adults with or without wings. If present, held above the abdomen, hind wing much smaller than front wing. (fig. 134) 14

)). Wings highly sculptured (fig. 131) 11
1'. Wings not sculptured 12

Figure 131.—Oak lace bug (*Corythucha arcuata*): A, adult
nymphs on bur oak.

11(10). Found on bur oak (fig. 131). Leaves discolored. In
present from mid to late summer. *Corythucha arc*
(Say) . . . . . **oak lace**

11'. Found on American elm and Siberian elm. Le
discolored. Insect present from mid to late sum
Corythucha ulmi Osborn & Drake . . . . . **elm lace**

12(10). Stippled discoloration on boxelder and Siberian elr
. 13

12'. Stippled discoloration on green ash (fig. 132a). V
light tan with pinkish markings (fig. 132b). I
present from June to October. *Neoborus amoenu*
(Reuter) . . . . . **ash plan**

ure 132.—Ash plant bug (*Neoborus amoenus*): A, damage; B, adult.

12). Found on Siberian peashrub. Insect red with black median stripe, wing tip black. Insects present from July to September. *Lopidea* sp . . . . . **a plant bug**

3'. Found on boxelder. Insect black with three longitudinal red lines on pronotum (fig. 133), wing edge marked with red. Insects present from August to October. *Leptocoris trivittatus* (Say) . . . **boxelder bug**

Figure 133.—Boxelder bug (*Leptocoris trivittatus*): A, adu
nymphs.

(9). Aphids on
Boxelder, Siberian peashrub 15
Cottonwood 16
Willow 17
American plum 18
Common chokecherry 19
Green ash 20
American elm 21

(14). Found on leaves and twigs of boxelder. Body light to dark olive green, cornicle pale green (fig. 134). *Periphyllus negundinis* (Thomas) ..... **boxelder aphid**

15'. Found on leaves and seed pods of Siberian peashrub. Body and cornicle (fig. 134) light green. *Acyrthosiphon caraganae* (Cholodkovsky) .... **caragana aphid**

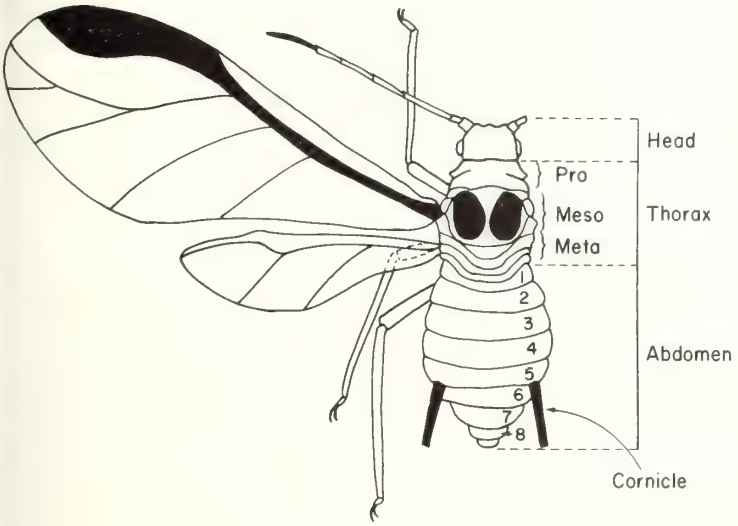


Figure 134.—Generalized drawing of a winged aphid.

16(14). Body greenish yellow, cornicle (fig. 134) short. Aphi
found on leaves and twigs of cottonwood. *Neoth*
masia populicola (Thomas)
. . . . . **cloudywinged cottonwood leaf ap**

16'. Body green to reddish brown, cornicle (fig. 134) lor
Aphids found on twigs of cottonwood. *Pterocomm*
populifoliae (Fitch) . . . . . **reddishbrown poplar apl**

17(14). Body yellow to dark reddish brown (plate 4; fig. 13
antenna hairy. Found on twigs of willow. *Pterocomm*
sp . . . . . **a willow apl**

17'. Body pale green, antenna (fig. 134) hairless. Found
leaves of willow. *Cavariella* sp . . . . . **a willow apl**

Figure 135.—A willow aphid (*Pterocomma* sp.) on white wi

18(14). Body dark brown, head and thorax dark brov
black, cornicle (fig. 134) present. Found on twig
curled leaves of American plum. *Aphis se*
(Thomas) . . . . . **rusty plum**

18'. Body yellowish green, head and thorax (fig. 134)
brown to black, cornicle absent. Found on twig
curled leaves of American plum. *Asiphonaphis*
Wilson & Davis . . . . . **a plum**

(14). Cornicle present, body light yellow to pale green (plate 4; fig. 134). Found on twigs and curled leaves of common chokecherry. *Aphis cerasifoliae* Fitch . . . . . **chokecherry aphid**

9'. Cornicle absent, body yellowish green, head and thorax (fig. 134) dark brown to black. Found on twigs and curled leaves of common chokecherry. *Asiphonaphis pruni* Wilson & Davis . . . . . **a plum aphid**

(14). Body pale green, antenna (fig. 134) shorter than 1/3 body length. Found in curled leaves of green ash. *Prociphilus fraxinifolii* (Riley) . . . . . **leafcurl ash aphid**

20'. Body brown, antenna (fig. 134) longer than 1/3 body length. Found on twigs of green ash. *Prociphilus venafuscus* (Patch) . . . . . **smokywinged ash aphid**

(14). Leaves with marginal leaf curl toward ventral surface (fig. 136). Body dark green to dusky gray. American elm. Aphids present from May to July. *Eriosoma americanum* (Riley) . . . . . **woolly elm aphid**

21'. Leaves with rosette-type curl (plate 7). Body yellowish to rusty brown. American elm. Aphids present from April to July. *Eriosoma lanigerum* (Hausmann) . . . . . **woolly apple aphid**

gure 136.—Damage of the woolly elm aphid (*Eriosoma americanum*) on American elm.

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APPENDIX

GLOSSARY

Anal: Pertaining to the last segment of the abdomen.

Caudal: Pertaining to the anal end of the insect body.

Cervical: Relating or belonging to the neck.

Cornicle: The terminal dorsal erect horns or rounded pro tions on aphids.

Dorsal: Of or belonging to the upper surface.

Elytra: The anterior leathery or chitinous wings of beet serving as coverings to the hind wings, commo meeting in a straight line down the middle dorsum in repose.

Facet: A small face or surface.

Flocculent: Consisting of soft flakes.

Frass: Solid excrement of insects; wood residue left boring insects.

Larva: An insect which hatches from the egg and di fundamentally in form from the adults.

Mesothorax: The second or middle thoracic segment which b the middle pair of legs.

Proleg: Any process or appendage that serves the purpo a leg; specifically the fleshy unjointed abdon legs of caterpillars and certain sawfly larvae.

Pronotum: The upper or dorsal surface of the prothorax.

Prothorax: The first thoracic segment which bears the ant pair of legs.

Punctate: Set with impressed points or punctures.

Rugosities: Wrinkles.

Scolus: Tubercles in the form of spinose projections o body wall of certain caterpillars.

e: Slender, hairlike appendages.

acle: Lateral openings on the segments of the insect body through which air enters.

ıre: The line of juncture between the elytra of a beetle.

rax: The second region of the insect body bearing the true legs and wings; made up of three segments: prothorax, mesothorax, and metathorax.

ercle: A small abrupt elevation of varying form; a little solid pimple or small button; in caterpillars, tubercles sometimes bear setae.

LIST OF TREES AND SHRUBS MENTIONED IN KEY

Common name	Botanical name
Boxelder	*Acer negundo* L.
Silver maple	*Acer saccharinum* L.
Saskatoon serviceberry	*Amelanchier alnifolia* (Nutt.) N
Paper birch	*Betula papyrifera* Marsh.
Siberian peashrub	*Caragana arborescens* Lamarch
Hackberry	*Celtis occidentalis* L.
Peking cotoneaster	*Cotoneaster acutifolia* Turczan
Russian-olive	*Elaeagnus angustifolia* L.
Green ash	*Fraxinus pennsylvanica* Marsh.
Tamarack	*Larix laricina* (Du Roi) K. Koc
Tatarian honeysuckle	*Lonicera tatarica* L.
Apple	*Malus spp.*
White spruce	*Picea glauca* (Moench) Voss
Blue spruce	*Picea pungens* Engelm.
Ponderosa pine	*Pinus ponderosa* Laws.
Scotch pine	*Pinus sylvestris* L.
Cottonwood	*Populus deltoides* Bartr.
Aspen	*Populus spp.*
American plum	*Prunus americana* Marsh.
Sand cherry	*Prunus pumila* L.
Common chokecherry	*Prunus virginiana* L.
Bur oak	*Quercus macrocarpa* Michx.
Rose	*Rosa spp.*
White willow	*Salix alba* L.
Willow	*Salix spp.*
Common lilac	*Syringa vulgaris* L.
American basswood	*Tilia americana* L.
American elm	*Ulmus americana* L.
Siberian elm	*Ulmus pumila* L.

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Stein, John D., and Patrick C. Kennedy.
1972. Key to shelterbelt insects in the northern great plains. USDA Forest Serv. Res. Pap. RM-85, 153 pp. Rocky Mountain Forest and Range Experiment Station, Fort Collins, Colorado 80521.

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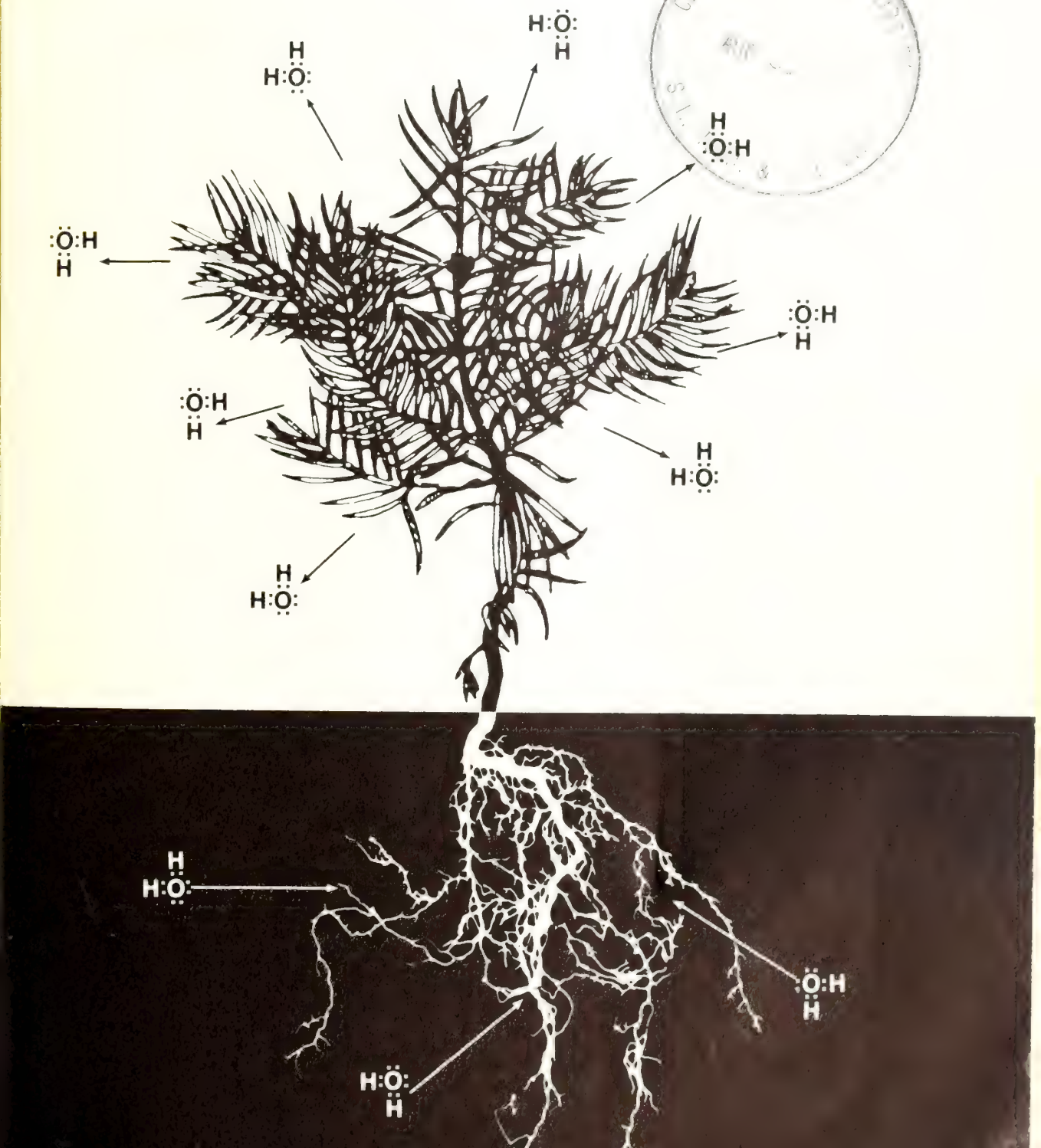
Moisture Stresses in Arizona Mixed Conifer Seedlings

by
John R. Jones

CLEMSON UNIVERSITY



ABSTRACT

Dry-season moisture stresses were measured in wild seedlings of Douglas-fir, ponderosa pine, Engelmann spruce, and corkbark fir. Seedlings less than about 15 cm (6 inches) tall had higher stresses than larger trees; above 15 cm size made no difference. Nighttime recovery was complete. There was no increasing trend of stresses through the dry season on sites and seedling sizes sampled, and day-to-day variability seemed a function of day-to-day weather differences. Species differences were small but significant. There are implications for planting and for the use of plant moisture stress measurements in classifying regeneration habitats.

Keywords: Habitat classification, seedling survival, seedling growth, regeneration, Pseudotsuga menziesii var. glauca, Pinus ponderosa, Picea engelmannii, Abies lasiocarpa var. arizonica, pressure bomb.

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April 1972

Moisture Stresses in Arizona Mixed Conifer Seedlings

by

John R. Jones, Plant Ecologist

Rocky Mountain Forest and Range Experiment Station[1]

[1]Forest Service, U. S. Department of Agriculture, with central headquarters maintained at Fort Collins, in cooperation with Colorado State University. Author is located at Flagstaff in cooperation with Northern Arizona University.

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Moisture Stresses in Arizona Mixed Conifer Seedlings

John R. Jones

Because much of the Southwest is arid or semiarid, some foresters feel that drying is the most critical source of regeneration failures in the region. But the Southwest has large climatic differences; those familiar with southwestern mixed conifer forests know how wet they often are. They also know the persistent dry and often windy weather that characterizes these mixed conifer forests in spring and early summer.

In this study, seedling moisture stresses were examined during the dry season in Arizona mixed conifer forest. The possibility of using plant moisture stress (PMS) was also explored as a tool in classifying regeneration habitats on the basis of physiographic factors or vegetation types.

Literature Review

Moisture stress measurements have been variously reported in atmospheres (atm) and bars. Bars are used here. Where atm were used in the literature reviewed, they have been converted here to bars (1 atm equals 1.013 bars).

Factors Affecting Stress

Any factors that influence vapor pressure deficits (VPD) in and adjacent to leaves should affect PMS; so should factors that influence moisture movement into and through plants. Thus Pierpoint (1967) found higher stresses on the exposed sides of pole-sized red pine (Pinus resinosa) than on the shady sides. When soils are not too dry, low nocturnal VPD result in low PMS. Stresses rise after sunup in response to rising VPD. When soils are dry enough, moisture uptake is slowed sufficiently that daytime stresses become severe and nighttime recovery is incomplete.

In Oregon, Waring and Cleary (1967) found that with adequate soil moisture, PMS in Douglas-fir (Pseudotsuga menziesii) neared its peak before 1000 hr., climbed slightly and irregularly until 1430, then dropped sharply, approaching their minimum by 2000.

Cleary (1969) also showed the increases of PMS as the Oregon dry season progressed. Stresses stayed low for a time, then climbed in a sigmoid curve. As early as the end of June there was little nighttime recovery on a very coarse granitic soil. In a fine-textured soil there was considerable recovery at night as late as August, although dawn minima in July and August exceeded 30 bars.

Stresses in plants are considerably higher than in the soils they grow on. Pierpoint (1967) found that pole-sized red pine on a soil "near field capacity" had stresses averaging 9.7 bars on a cool, still, hazy day. On a bright day, trees growing on soils near field capacity can have stresses of 20 bars (Waring and Cleary 1967). The soil moisture stress at field capacity is 0.3 bar.

Waring and Cleary also pointed out that when trees 1 m tall had stresses nearing 40 bars, 25-m trees had stresses of 20 bars, presumably because the larger trees tap deeper soil layers where there is more water.

Effects on Trees

Judging from the literature as a whole, well hydrated trees have stresses below 8 bars.

Waring and Cleary (1967) reported that different coniferous species in Oregon had similar PMS when growing together, but that the stresses they could survive seemed to be different. Other studies also indicate that lethal stress levels vary among coniferous species (Pierpoint 1967, Kaufmann 1968, Cleary 1969).

Data in Cleary (1969) suggest, but do not establish, that duration of high stresses may be important.

Moisture stresses far short of lethal have strong effects on growth and may influence survival indirectly. Brix (1962) found that photosynthesis in loblolly pine seedlings (Pinus taeda) began to decrease at a PMS of only 4 bars, and stopped at 11 bars. Respiration began to decrease at 7 bars.

Seedling growth rates of several coniferous species decreased sharply with small soil moisture deficits (Jarvis and Jarvis 1963, Stransky and Wilson 1964). Height growth of potted

shortleaf (Pinus echinata) and loblolly pines stopped entirely when soil moisture stresses (SMS) increased to only 3.5 bars. In contrast, Glerum and Pierpoint (1968) found seedling height growth of several Canadian conifers not seriously reduced by SMS as high as 15 bars. They suggested that the seeming incompatibility of their results with others may have been due to the brevity of their stress periods, and also pointed out the importance of timing relative to the period of maximum elongation.

Unfortunately, SMS can be translated into PMS only very loosely. Plant moisture stresses not only have a much greater daily range and sensitivity to transient atmospheric conditions; they also vary on different soils having the same soil moisture stress (Knipling and Miller 1965).

Moisture Environment of the Study Area

The study area is in the White Mountains of eastern Arizona. Elevations range from 2,700 to 2,800 m (8,900-9,200 feet). May and June have low relative humidities, abundant sunshine, much wind, and very little rain. Rai usually become frequent before mid-July, a sometimes in late June. The rest of the su mer has abundant cloudiness. Measurable r falls on about 50 percent of July and Aug days, and usually there are not more thar few consecutive days without measurable ra

The moisture regime is characterized figure 1. The diagram assumes a soil moist retention capacity of 100 mm (4 inches)—app priate for the rooting zone of well-develop seedlings in the gravelly silty loam soils p dominant in the area. It also assumes a co plete grass cover. Perhaps the most striki feature of the climate is the surplus of r over potential evapotranspiration during J and August, partly the result of temperatu that rarely reach 27° C (80° F) and frequen stay below 21° C (70° F) throughout the d

The 1970 dry season was near norm On March 30, though south slopes were mos bare, the general snowpack contained 7.8 incl of water, close to the 1964-71 average of inches for that date. After 14 mm (0.54 in of water fell on April 17 and 18, only 16.5 n (0.65 inch) more fell until June 23. Signific scattered showers began on June 23 and beca frequent on July 1.

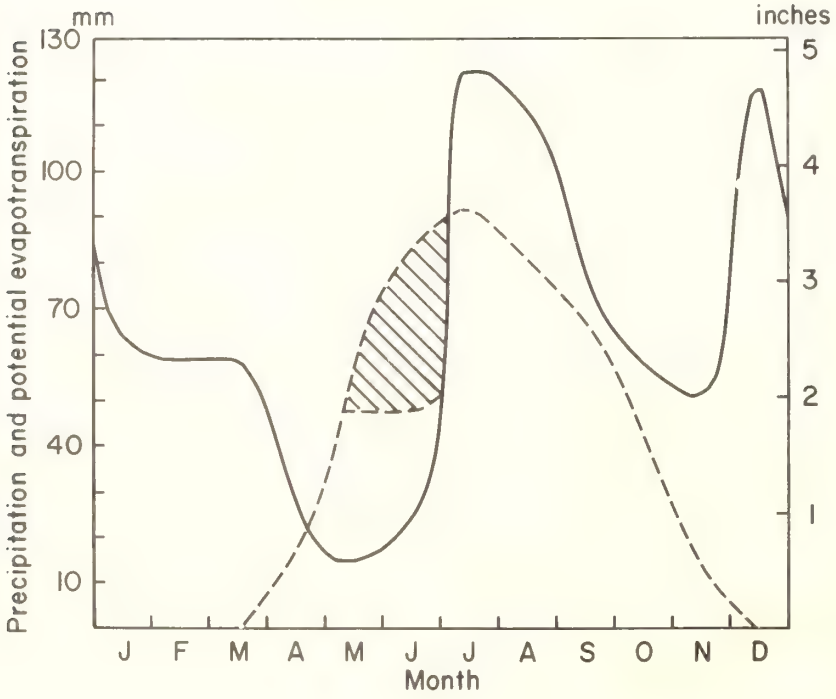

Figure 1.—Moisture regime. Solid indicates precipitation, broken potential evapotranspiration Hachured area indicates moi deficit; its depth below br line, amount of deficit (after Th thwaite and Mather, 1957).

In the same locale, soil moisture was studied
der grass and bare surfaces on clearcut
rtherly, level, and southerly slopes (Embry
1). Below the surface inch or two, SMS
ached or approached the permanent wilting
int (15 bars) only on level and southerly
ping grassy plots. Under bare surfaces and
grassy north slopes no stresses were meas-
ed higher than 2.5 bars.

Methods

Stresses were measured with a portable
ssure chamber. Measuring procedures were
sentially those described by Waring and Cleary
67). Daytime stresses in open-grown trees
re from twigs exposed to the sun, unless
erwise specified. Also unless otherwise
cified, stresses in trees not in the open
re measured in shaded twigs, because in
ny trees all twigs were shaded and this prac-
reduced variation within an experiment.
urs are given in standard time.

A number of simple experiments were made
explore a number of relationships. Instead
describing the different methods here, they
be described briefly in connection with
results.

Results

Measured stresses did not approach those which the literature indicates are critical. Nor was there any sign of failure to recover fully at night. The highest midday stress measured was 22 bars in an Engelmann spruce (Picea engelmannii) that had had a dawn stress of only 5.3 bars. Nighttime recovery often brought individual stresses below 5.5 bars and occasionally to 4 bars.

Seedling Size

On May 20 and June 9, stresses measured in Engelmann spruce from 13 cm (5 inches) to 12 m tall were unrelated to height.

On June 17, stresses were measured in cork bark fir (Abies lasiocarpa var. arizonica) in a selectively cut stand, with the sample concentrated in the smaller seedling classes. Those shorter than 15 cm (6 inches) tended to have somewhat higher stresses than larger seedlings (fig. 2).

On July 3, after several showers had fallen and the soil was near field capacity, stresses in Douglas-fir as small as 7.6 cm (3 inches) were unrelated to height.

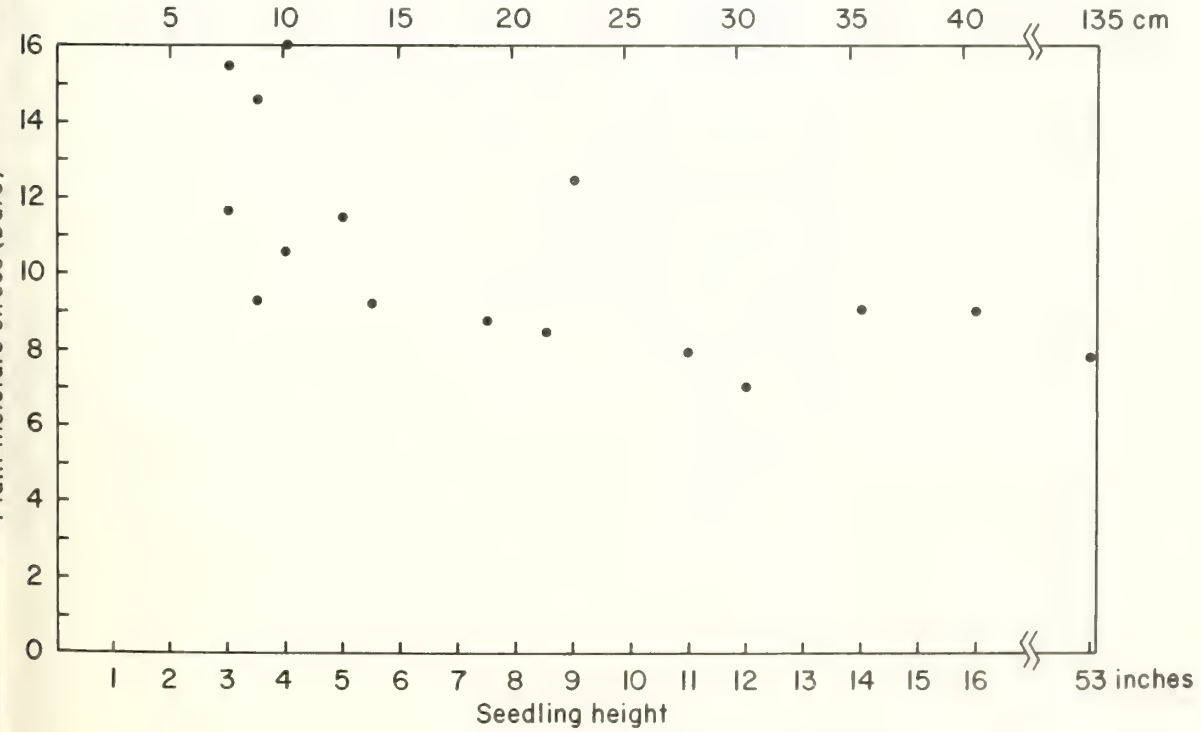

Figure 2.—Relation of plant moisture stress to corkbark fir seedling height, June 17.

Changes During the Season

Midday stresses in ponderosa pine seedlings were measured periodically on a nearly level clearcutting with a very gravelly loam soil. Grass was sparse and short.

All the stresses shown (fig. 5), except those on May 26, are from seedlings that had been in the sun for several hours. The stress differences on different days are highly significant, statistically, but do not form an ascending series such as Cleary (1969) demonstrated for southwestern Oregon during the much longer, warmer dry season there. Most of the seedlings in this experiment were 5 or 6 years old, and ranged from 18 to 92 cm tall (7-36 inches). Smaller seedlings in heavy grass might have shown an increasing trend.

The day-to-day differences in plant moisture stress shown in figure 5 seem due to weather differences. On May 21, when the highest stresses were measured, the wind was stronger than at any subsequent measurement in this experiment, and the relative humidity was 33 percent. Five dry days later, measurements taken under heavy clouds were the lowest in the series; the air was still and the relative humidity 60 percent. Later that day a heavy shower fell. Two days later, with the sun shining, stresses were significantly higher again, although the upper soil had been thoroughly rewetted.

At the end of July, with the entire soil profile near or above field capacity, stresses late on a sunny morning were only a little lower than on similar sunny days during the dry season.

A series of dawn stress measurements in the clearcutting showed that nighttime recovery levels did not change during the dry season. Averages ranged from 7.2 to 7.6 bars.

Effects of Grass and Elevation

Effects of grass and elevation were not established. No area of heavy grass was found with enough seedlings for a comparison. An area of moderate grass cover was compared with an area of sparse grass 7 km away. Stress differences in 6-year-old ponderosa pine were trivial.

Stress differences in 6-year-old ponderosa pine also were trivial when two otherwise similar areas differing in elevation by 460 m (1500 feet) were compared.

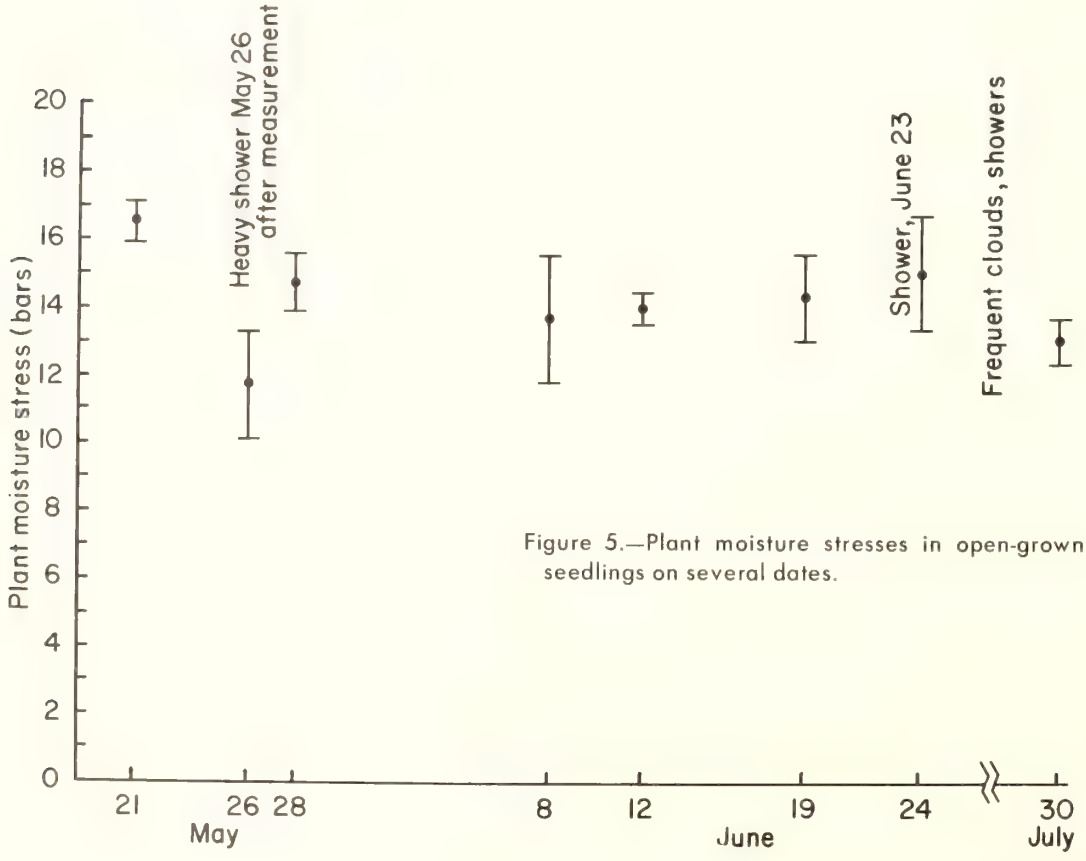

Figure 5.—Plant moisture stresses in open-grown ponderosa pine seedlings on several dates.

Discussion

Several factors might tend to cause higher plant moisture stresses in other mixed conifer areas in the Southwest. These include coarser soils, lighter snowpacks, lower elevations, higher temperatures, and delayed and less frequent summer rains.

Survival

The rather low plant moisture stresses measured indicate that spring dry-season effects are not so severe as commonly thought. We have no measurements from those conditions most likely to be critical, however, nor the seedling sizes most likely to be seriously affected. Few seedlings were found in grassy clearcuttings, and most clearcuttings in the White Mountains are grassy. Seedlings less than about 6 cm (2.5 inches) tall (typical 3-yr-olds) could not be used in our bomb.

It was encouraging to find no severe moisture stresses in seedlings of planting-stock size. Soil moisture data from the same locale indicate that, at soil depths accessible to planting stock, moisture supplies normally are suitable for survival (Embry 1971). Known exceptions are soils with heavy grass cover on both level ground and southerly slopes, where the permanent wilting point was reached or approached from the surface to the greatest depth sampled—40 cm (16 inches). Newly transplanted seedlings may be handicapped, however; because of lifting, handling, and so forth, their root systems may not extract water with normal efficiency during the first growing season.

Function and Growth

For a period of 5 to 8 hr, beginning about 0800, moisture stresses measured in stems were above 11 bars, even in cloudy weather. Brix (1962) found that loblolly pine seedlings stopped photosynthesizing when stresses in **needles** reached 11 bars. Respiration was also reduced. This suggests that photosynthesis in mixed conifer seedlings, too, may be zero during a considerable part of the day. According to Pitchie and Hinckley (1971) however, moisture stresses measured in needles of some coniferous species are often several bars lower than those measured in stems.

No data were obtained relating seedling growth to plant moisture stresses in mixed conifers. Where soil moisture stresses are high, however, the literature suggests that seedling growth is restricted. Growth reduction exposes seedlings for a longer time to serious injury or death from rodents, soil insects, cattle, deer, and elk.

Habitat Classification

There seem to be two main approaches available for classifying regeneration habitats. One is to develop a continuum model of regeneration habitats and classify by subdividing the model. Plant moisture stress might be a useful tool in modeling the moisture regime. The other approach is to classify vegetation site types or physiographic site types directly. Here, plant moisture stress might be used to test and to refine or modify the types.

Although this study neither established nor disproved the usefulness of plant moisture stress for classifying regeneration habitats in the southwestern mixed conifers, it did indicate the following limitations and directions:

1. Except for the true firs (Abies) and some southwestern white pine (Pinus strobiformis), the seeds of almost all southwestern mixed conifers germinate after the summer rains begin. Those summer germinants face their first spring dry season with root penetration averaging as little as 6 cm and as much as 20 cm (2.4-8 inches), depending on the species. Limited study indicates they do not penetrate much deeper until the third or fourth growing season (Jones 1971).

   Consequently, in classifying moisture regimes for natural regeneration, we need to know the stresses experienced by seedlings during their first two or three dry seasons, seedlings mostly less than 5 cm (2 inches) tall. Larger seedlings cannot be used to characterize the stresses in such small seedlings.

   Even the smallest seedlings used in this study recovered well at night, so dawn stresses seem less promising than midday stresses for use in the White Mountains. And measurements of midday stresses in very small seedlings will have to be somewhat more sensitive to habitat differences than stress measurements in the seedling sizes used here. Otherwise habitat differences will be obscured by other factors.

2. If several locations are to be measured the same day, to minimize effects of day-to-day weather differences, it will be desirable to have two or more pressure bombs operating at different locations. Otherwise, travel time, combined with the number of seedlings needed to characterize the site adequately and the time required per seedling, would spread the readings over too much of the day.

3. The frequent shortage or absence of suitable seedlings where they are wanted makes artificial seeding seem necessary for test stock. That should also give maximum uniformity. Species differences need to be considered, and artificial seeding permits use of selected species.

4. The available mixed conifer clearcuttings do not sample the mixed conifer habitats at all adequately, so sampling in forest stands seems necessary.

5. At lower mixed conifer elevations, Engelmann spruce and corkbark fir are usually absent, and ponderosa pine seedlings do poorly under the canopy. White fir and corkbark fir germinate in the spring, and many die. White pine, ponderosa pine, and the surviving white firs root somewhat more deeply the first year than do Douglas-fir, the spruces, and corkbark fir. Douglas-fir is the most widespread of the mixed conifers, and in many parts of the Southwest the most abundant. These considerations suggest Douglas-fir as best suited for habitat classification work.

Primary Management Significance

This study has a major management implication, especially when considered in conjunction with (1) Embry's (1971) soil moisture study, (2) what is known of seedling rooting depths (Jones 1971), and (3) what has been learned from studies in progress. In loamy soils in the White Mountains, and presumably in other areas with similar moisture regimes, drought is normally not a major factor in seedling survival beyond age two, and in pines, not even in the first dry season, except where there is grass cover. Moderate grass cover does not cause serious moisture stresses in seedlings as well rooted as 6-yr-old ponderosa pine.

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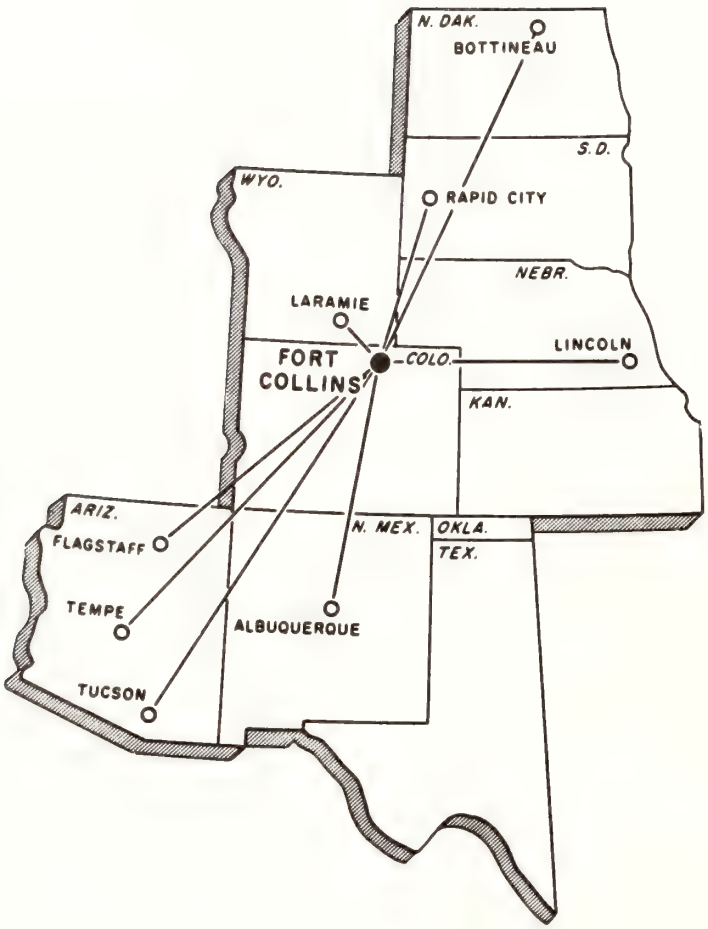
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Simulating Yields of Southwestern Ponderosa Pine Stands, Including Effects of Dwarf Mistletoe

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Abstract

Presents a procedure for computation of yield tables for diseased even-aged stands of ponderosa pine in Arizona and New Mexico. Stand age at time of initial infection by dwarf mistletoe may be varied as desired. Other control variables include stand age at initial thinning, stocking goals, frequency of thinning, and regeneration system. Stand conditions and severity of dwarf mistletoe infestation change with time and in response to intermediate cuttings.
Keywords: Stand yield tables, timber management, forest management, simulation, Arceuthobium vaginatum, Pinus ponderosa.

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Simulating Yields of Southwestern Ponderosa Pine Stands, Including Effects of Dwarf Mistletoe

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Computation procedures for predicting elds and a computer program SWYLD that ints yield tables are described for even-aged ands of southwestern ponderosa pine (Pinus nderosa Laws.). Details of field work and mputations that apply to healthy stands of nderosa pine have been presented elsewhere Myers 1971). Such procedures will not, how-er, provide some items of information essential r decisionmaking in the Southwest. For actical application, important and predictable uses of reduced growth and mortality should e included in the computations. One such use is included here.

Dwarf mistletoe (Arceuthobium vaginatum bsp. cryptopodum (Engelm.) Hawks. & Wiens) widespread in southwestern ponderosa pine rests. Andrews and Daniels (1960) found this warf mistletoe on 36 percent of some 2,700 nderosa pine plots located throughout Ari-na and New Mexico. In the Lincoln National rest and adjacent Mescalero Apache Reserva-n in southern New Mexico, the infection rate as over 50 percent (Andrews and Daniels 60, Hawksworth and Lusher 1956).

Several studies have documented the ad-rse effects of dwarf mistletoe on the height d diameter growth of individual ponderosa nes (Korstian and Long 1922, Sperry 1934, awksworth 1961). Such studies do not, how-er, reveal the total stand loss due to dwarf istletoe. They do not report mortality, but ve information on surviving trees only.

Dwarf mistletoe is one of the four major uses of mortality in southwestern ponderosa ne (Myers and Martin 1963, Pearson 1939). earson (1938) found mortality in heavily in-sted cutover stands to be about five times at in comparable lightly infested or healthy ands. On the Mescalero Apache Reservation, ew Mexico, mortality in stands with dwarf istletoe was nearly twice as high in infested ands as in healthy stands (Hawksworth and usher 1956). The differences were most pro-nounced in cutover areas, where the mortality te in infested stands was 3.3 times that in istletoe-free stands.

In the all-aged stands of Grand Canyon ational Park, mistletoe-caused mortality and owth reduction offset 10-year basal area growth moderately and heavily infested stands (Lightle 1966). In pole-sized stands on the Mescalero Reservation, however, basal area declined during a comparable period only in heavily infested stands.

The studies referred to above dealt primarily with the cumulative effects of dwarf mistletoe in unmanaged stands. They do not provide data that can be used directly for yield prediction in managed stands or for comparisons of alternatives. To obtain the necessary pine-mistletoe relationships, procedures used in lodgepole pine stands (Myers, Hawksworth, and Stewart 1971) were repeated in the Southwest.

Information Used

Field and office procedures used to obtain the relationships in program SWYLD were similar to those outlined by Myers (1971) for healthy stands. Additional information on pine-dwarf mistletoe interactions was obtained from several temporary and permanent plots. Most data were from a yield study [2] based on 55 transects located throughout the ponderosa pine forests of Arizona and New Mexico. Additional information was obtained from permanent plots at Fort Valley Experimental Forest and Grand Canyon, Arizona, and the Mescalero Apache Reservation, New Mexico. Derivations of functions that include measures of infection by dwarf mistletoe are described briefly below and in detail elsewhere (Myers et al. 1971).

Basal area and other per-acre values, average stand diameter, and site index (Meyer 1938) are used as dependent and independent variables to obtain the prediction equations used in program SWYLD (appendix 1). The equations shown as FORTRAN statements in the program listing contain only significant independent variables. They indicate the possible appearance of similar functions for other species or localities.

Items computed from field data and uses made of them in SWYLD are as follows:

[2] *Hawksworth, F. G., P. C. Lightle, and T. E. Hinds. Effects of dwarf mistletoe on growth and yields of ponderosa pine. (Manuscript in preparation at Rocky Mt. Forest and Range Exp. Stn.)*

1. Equations to estimate mortality in healthy (OUT) and diseased (DIE) stands are computed from density, mortality, and other data.

2. Prediction equations for height (HTSO) are determined from healthy stands with densities within the range of possible management goals. Infected plots provide data used to derive the equation for reduction in height growth due to disease (PCT).

3. Initial average diameters and other variables from healthy stands are used to obtain the equation for average d.b.h. after 10 years (DBHO). Data from diseased stands provide the equation for reduction in diameter growth due to dwarf mistletoe (TEM). Average stand diameter is the diameter of the tree of average basal area.

4. Cubic- and board-foot volumes per acre are computed from tree volume equations (Myers 1963). Total cubic volumes then provide equations for stand volume in cubic feet (TOTO and TOTT). Total volumes plus merchantable cubic- and board-foot volumes are used to obtain equations for the volume conversion factors (FCTR and PROD) computed by subroutine SWVOL.

5. Several prediction equations are used to obtain dwarf mistletoe ratings (DMR) in SWYLD. One equation for DMR predicts the initial rating if the stand has never been thinned. Other equations for DMR predict the current rating as an increase from a past value. An expected post-thinning rating (DMRT) is computed if infection index is not so high (3.0 or greater) as to make thinning impractical, and if the stand has not already been thinned from above. An equation in subroutine SWCUT2 then predicts the percentage of trees to be removed by thinning from above (REDT) to obtain the expected rating. For subsequent thinnings, DMRT is computed from intensity of thinning and rating prior to thinning.

   Computation of ratings by SWYLD begins with use of the variable START. This is the average of the tree ages when each part of the stand is first infected. It is not the age when the first tree in the stand is infected.

6. Thinning intensity in healthy stands, or in stands to be thinned from below, is based on a relationship between d.b.h. and basal area. Basis for the computations is given in the following tabulation:

Average stand d.b.h. after thinning (Inches)	Basal area per acre (Sq. ft.)
2.0	12.1
2.5	17.9
3.0	23.7
3.5	29.5
4.0	35.2
4.5	41.0
5.0	46.8
5.5	51.8
6.0	56.6
6.5	61.2
7.0	65.4
7.5	69.2
8.0	72.5
8.5	75.3
9.0	77.5
9.5	79.1
10.0+	80.0

These values, SQFT in subroutine SWCUT1 and SWCUT3, represent one possible series of densities that could be used to guide successive thinnings. The growing stock level shown above is 80; reserve basal area remains constant at 80 square feet after stand d.b.h. reaches 10.0 inches. Other stocking levels are named the same way. For example, level 100 means that reserve basal area will be 100 square feet when d.b.h. is 10.0 inches or larger. Basal area for level 100 and diameters smaller than 10.0 inches are obtained by multiplying each basal area of level 80 by the amount 100/80. Values for any stocking level, THIN or DLEV in SWYLD, are computed similarly.

Equations for DBHP in subroutine SWCUT1 and SWCUT3 also describe the tabulated values. In this case, diameter is estimated when basal area and the desired stocking level are known. Variables BREAK and BUST indicate points where the relationship of diameter on basal area has been broken into segments for convenience in regression analysis.

Growing stock levels to be left after thinning from below are indicated by assigning values to THIN and DSTY on data card type 4, as shown in the listing of Order and Contents of the Data Deck. Each assigned value is a growing stock level or the basal

area left when d.b.h. after thinning is 10.0 inches or greater.

Equations for DBHE (used as DBHT) in SWCUT1 and SWCUT3 and for ADDHT in the main routine are derived from data obtained in a variety of thinned stands. Thinnings could also be simulated on a computer to obtain data for the DBHE and ADDHT equations (Myers 1971).

Values for AGEO, DBHO, and DENO on data card type 4 are obtained by examining numerous young stands. Average d.b.h. at various ages is determined for each site class and for each of several levels of stand density. These data are gathered by users of the program to partially describe their management objectives.

Description of Program SWYLD

Program SWYLD consists of a main program and four subroutine subprograms. The main program performs most computations and writes the yield tables. Three subroutines compute average stand d.b.h. and stand density after thinning. The fourth subroutine computes factors that are used in the main program to convert total cubic feet to other units.

Operations performed by each routine are identified by the comment statements of the source program (appendix 1). Initial stand conditions and values of several control variables are read into computer memory in the order and format given in the tabulation of Order and Contents of the Data Deck. Zero punches in any data card except card type 5 will cause control to move to the end of the program, a diagnostic message to be printed, and termination of the job. The number of yield tables computed and printed is determined by the values assigned NTSTS on card type 1 and MIX on card type 3. NTSTS is the number of sets of tables to be produced. MIX is the number of tables in a set or the number of growing stock levels (DLEV) tested.

Order and Contents of the Data Deck

Card type	Number of cards	Variable name	Columns	Format	Description of variable
1	1	NTSTS	1-4	I4	Number of tests per batch. The number of sets of yield tables to be produced.
2	1	COMCU	1-8	F8.3	Minimum cut in merchantable cubic feet to be included in total yields. Must be at least 1.0.
		COMBF	9-16	F8.3	Minimum cut in board feet to be included in total yields. Must be at least 1.0.
3	1 per test	JCYCL	1-4	I4	Interval between intermediate cuts. A multiple of RINT.
		MIX	5-8	I4	Number of stocking levels or values of DLEV to be examined in one test.
4	1 per test	AGEO	1-8	F8.3	Initial age to be shown in a yield table. Stand age when first thinning occurs.
		DBHO	9-16	F8.3	Average stand d.b.h. just prior to initial thinning at stand age AGEO.
		DENO	17-24	F8.3	Number of trees per acre just prior to initial thinning at stand age AGEO.

Card type	Number of cards	Variable name	Columns	Format	Description of variable
		DSTY	25-32	F8.3	Lowest growing stock level for intermediate cuts after initial thinning. Level will increase by 10 as many times as specified by MIX on card type 3.
		RINT	33-40	F8.3	Number of years for which growth and infection equations make one projection of growth or change. Value is 10.0 for the equations given in appendix 1.
		SITE	41-48	F8.3	Site index on which the set of yield tables is to be based.
		THIN	49-56	F8.3	Growing stock level for initial thinning at age AGEO. May equal DLEV.
		START	57-64	F8.3	Stand age at which dwarf mistletoe infection begins. Never enter zero. Enter number larger than largest REGN(I) if infection will not occur during the rotation.
5	1 per test	REGN(1)	1-8	F8.3	Stand age at which first regeneration cut will occur. Must never be zero or blank, as this is rotation length for clearcutting.
		VLLV(1)	9-16	F8.3	Percentage of previous DLEV to be left at age REGN(1). Will be zero with clearcutting. Enter as a decimal.
		INVL(1)	17-24	F8.3	New interval between cuts in effect after age REGN-(1). Will be zero with clearcutting.
		REGN(2)	25-32	F8.3	Stand age at which second regeneration cut, if any, will occur. Removal of seed trees or second cut of shelterwood.
		VLLV(2)	33-40	F8.3	Percentage of previous DLEV, including effect of VLLV(1), to be left at age REGN(2). May be zero. Enter as a decimal.
		INVL(2)	41-48	F8.3	New interval between cuts in effect after age REGN-(2). May be zero.
		REGN(3)	49-56	F8.3	Stand age at which third regeneration cut, if any, will occur. Final cut of 3-cut shelterwood.

Subsequent operations are performed in the following order:

1. Computation of average height, basal area, volume, and mistletoe rating just prior to initial thinning.

2. Change of interval between cuttings and of residual stand density if a regeneration cut is due and if changes are needed. Entries on data card type 5 control the changes. If the stand is to be clearcut, stand age at time of clearcutting or REGN(1) is the only entry needed. Seed-tree cutting requires that values for all items to and including REGN(2) be punched in card type 5. REGN(1) is stand age at first regeneration cutting and REGN(2) is age of the seed trees when they are removed. The interval between these two cuttings is INVL(1). Up to three regeneration cuttings are possible with the shelterwood system. Stand age at final cut will be REGN(2) for two-cut shelterwood and REGN(3) for three-cut shelterwood. If a regeneration cut is scheduled, it will be made in the same steps as described below for thinnings.

3. Thinning and computation of the new mistletoe rating after thinning, if the current rating is below 3.0. If thinning is possible, subroutines compute the new stand density and average d.b.h., as explained below. The main program then computes the new average stand height.

4. Computation of post-thinning volumes.

5. Computation of amounts removed by thinning and of values describing conditions before and after thinning.

6. Printing of before- and after-thinning values in the yield table.

7. Advancement of d.b.h., height, stand density, and mistletoe rating one prediction period and computation of new volumes. Mistletoe rating is computed as an increase from a previous value or as a projection from initial infection, depending upon whether or not thinning has occurred since infection.

8. Printing of values appropriate to the stand age, if thinning is not scheduled.

9. Rethinning, if thinning is scheduled, by return of program control to the operations described in item 2.

10. Repetition of operations described in items 2 to 9, inclusive, until stand age reaches the limit set by the largest value of REGN(I) on data card type 5.

Only one thinning in diseased stands will be from above, as simulated by SWCUT2. Subsequent thinnings in diseased stands will increase average d.b.h. and height, but by lesser amounts than in healthy stands where the smaller trees make up a larger percentage of those removed. This effect has been observed in subsequent thinnings of actual stands, and is simulated by SWCUT3.

Subroutines SWCUT1 and SWCUT3 compute average stand d.b.h. after thinnings that remove many of the smaller trees and thus increase average stand diameter and height. Successive percentages of trees to be retained (PRET) are tested until the relationship between d.b.h., basal area, and number of trees is mathematically correct and d.b.h. and basal area agree with the growing stock level specified by THIN or DLEV. Two major loops are provided in the subroutines because two equations are needed for estimating post-thinning d.b.h. (DBHE).

Subroutine SWCUT2 uses thinning standards based on the goals of sanitation thinning, not on THIN or DLEV. The reduced infection rating to be attained (DMRT) is computed by the main program as a function of average stand d.b.h., as follows:

D.b.h. (Inches)	Rating
2	0
4	0.5
6	1.0
8	1.5
10	2.0

SWCUT2 then computes the reduction in stand density (REDT) needed to attain this goal, based on d.b.h. and rating just prior to thinning. D.b.h. after thinning (DBHT) can then be determined directly with the same equations as for DBHE in SWCUT1. Successive approximations are unnecessary because percentage of trees to be retained (PRET) is known before DBHE (as DBHT) is computed.

Replacement of several statements will modify the program for other utilization standards, species, or regions. Replacements needed are:

1. Statements for SQFT, DBHP, BREAK, BUST, and related computations that contain the ratio of DLEV or THIN to 80.0, if desired. This change is needed if standards for reserve stands in SWCUT1 and SWCUT3 will be different from those shown in the tabulation of the previous section.

2. Statements from TOTO and TOTT, to make cubic volumes per acre correct for the species and tree volume equations selected.

3. Statements for FCTR and PROD in subroutine SWVOL that are correct for the species, tree volume equations, and utilization standards selected.

4. Statements for HTSO, ADDHT, and PCT so that height growth, changes in height due to thinning, and reductions in growth caused by dwarf mistletoe will be appropriate for the species.

5. Statements for or that include DMR, DMRT, and REDT; to show correct relationship for the host-parasite interaction being simulated.

6. Statement for DBHO, based on a growth study in healthy stands of the species of interest, and a statement for TEM to compute the effect of mistletoe on diameter growth.

7. Statements for DBHE in subroutine SWCUT1 and SWCUT3 and for DBHT in SWCUT2 that apply to the species of interest.

8. Statements that describe periodic losses in numbers of trees in both healthy (OUT) and diseased (DIE) stands.

9. Table headings.

A Sample Problem

The following sample problem provides additional description of the data deck and of the output (appendix 2). It can also serve as a test problem to check accuracy of punching of the source deck and to test compatibility with local equipment.

Assume a forest composed of even-aged stands of ponderosa pine that differ in degree of infection by dwarf mistletoe. Problems to be solved by the manager of such a forest include:

1. What growth can be expected in healthy stands of known site quality for various combinations of thinning frequency and intensity?

2. How is this growth affected by various degrees of dwarf mistletoe infection and time of initial sanitation thinning?

3. On the basis of potential yields of each stand, is thinning, replacement, or no treatment appropriate for the stand at this time?

4. Does each treatment decision appear appropriate when impacts on other forest resources are considered?

Answers that contribute to good land management cannot be obtained unless all numerical results can be estimated to a useful degree of accuracy. Program SWYLD provides such estimates for trees and dwarf mistletoe. In the sample problem, yields of healthy stands are compared with those initially infected at age 10. Other variables remain constant for both tests except for stand conditions at initial thinning and intensity of thinning. No scheduled thinning will be performed if the dwarf mistletoe rating is 3.0 or greater. Regeneration will be by two-cut shelterwood with 20 years between removal and final cut. The data deck contains the following values:

NTSTS - 3, for healthy stands (test 1), diseased and thinned at age 30 (test 2), and diseased and first thinned at age 50 (test 3).
COMCU - 320.0 cubic feet, minimum commercial cubic-foot cut.
COMBF - 1500.0 board feet, minimum commercial board-foot cut.
JCYCL - 20 years.
MIX - 3, or 3 intensities of thinning will be examined in each test.
AGEO - 30.0 years for two tests and 50.0 years for the third.
DBHO - 4.8 inches for two tests, 6.2 inches for the third.
DENO - 950.0 trees for two tests, 575.0 trees for the third.
DSTY - 80.0, lowest subsequent thinning leve of the 3 to be examined.
RINT - 10.0 years, prediction period of th equations.
SITE - 70.0 feet, base 100 years.
THIN - 100.0 level for initial thinning.
START - 200.0, 10.0, and 10.0 years on typ 3 data cards of test 1, test 2, an test 3, respectively. Any numbe larger than the largest value of REGN (I) could replace the 200.0 showr
REGN(1) - 110.0 years, stand age at time c removal cut.
VLLV(1) - 50.0 percent, read as a decima amount of previous residual basa area to be left as shelterwood.
INVL(1) - 20 years, interval between remova and final cuts.
REGN(2) - 130.0 years, stand age at time c final cut.

These values will provide data for comparison of the differences in yields betwee healthy and diseased stands, and between diffe ent types of diseased stands. Values must b read from data cards assembled in the orde

1) type 1, (2) type 2, (3) type 3 of test 1, 4) type 4 of test 1, (5) type 5 of test 1, (6) ype 3 of test 2, (7) type 4 of test 2, (8) type of test 2, (9) type 3 of test 3, (10) type 4 f test 3, and (11) type 5 of test 3. Additional ests could be made to examine the effect of ariations in thinning intensity or in any other ontrol variable.

Tables produced by SWYLD can be used n many ways to assist in decisionmaking. or many purposes, yields of healthy stands ill be desired so that long-range goals can e determined. Yields, numbers of noncom-ercial cuts, number of scheduled cuts that nnot be made, and size of the average tree e some of the values produced. Money elds and rates earned can be computed if ecessary data on costs and stumpage values e available. Stand ages at culmination of ean annual increment, and rates earned can lp the manager determine suitable rotations r his working groups.

A manager examining the tables in appendix for example, might reach the following con-sions:

1 A stand initially infested at age 10 and then left untreated for 40 years will produce very little merchantable volume by age 130. The stand is already too heavily infested by age 50 for subsequent treatment to produce improvement.

2 A stand infested by dwarf mistletoe at age 10 but thinned at 20-year intervals beginning at age 30, can produce only a small volume of useful wood products. Yields, including thinnings, would be much less than those from healthy stands with the same site index and thinned according to the same schedule. Also, actual yields of diseased stands would be less than the computed volumes because no reduction has been made for amounts of wood lost due to pitch or distorted grain.

3 In healthy stands, largest yields would be produced with relatively light thinnings, such as to level 100. Comparing yields in thinned stands with and without dwarf mistletoe, diseased stands produce about a third of the merchantable cubic- and board-foot vol-umes of healthy stands.

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APPENDIX 1
Listing of Program SWYLD

```
      PROGRAM SWYLD
     1(INPUT,OUTPUT,TAPE5=INPUT,TAPE6=OUTPUT)
C
C  TO COMPUTE AND PRINT YIELD TABLES FOR EVEN-AGED STANDS OF SOUTHWESTERN
C  PONDEROSA PINE WITH OR WITHOUT INFECTION BY DWARF MISTLETOE.
C
C  DEFINITIONS OF VARIABLES.
C
C      ADJHT  = INCREASE OR DECREASE IN AVERAGE STAND HEIGHT BY THINNING.
C      AGEO = INITIAL AGE IN YIELD TABLE.
C      BASO = BASAL AREA CUT PER ACRE.
C      BASB = BASAL AREA PER ACRE BEFORE THINNING.
C      BAST = BASAL AREA PER ACRE AFTER THINNING.
C      BDFC = BOARD FEET CUT PER ACRE.
C      BDFO = BOARD FEET PER ACRE BEFORE THINNING.
C      BDFT = BOARD FEET PER ACRE AFTER THINNING.
C      CFMC = MERCHANTABLE CU. FT. CUT PER ACRE.
C      CFMO = MERCH. CU. FT. PER ACRE BEFORE THINNING.
C      CFMT = MERCH. CU. FT. PER ACRE AFTER THINNING.
C      COMBF = MINIMUM COMMERCIAL CUT, BOARD FEET.
C      COMCU = MINIMUM COMMERCIAL CUT, CU. FT.
C      DBHO = AVERAGE STAND D.B.H. BEFORE THINNING.
C      DBHT = AVERAGE STAND D.B.H. AFTER THINNING.
C      DENC = TREES CUT PER ACRE.
C      DENO = TREES PER ACRE BEFORE THINNING.
C      DENT = TREES PER ACRE AFTER THINNING.
C      DIE  = TREES LOST IN DISEASED STANDS IN 10 YEARS, IN PERCENT.
C      DLEV = GROWING STOCK LEVEL FOR INTERMEDIATE CUTS AFTER THE FIRST.
C      DMR  = DWARF MISTLETOE INFECTION RATING.
C      DMRT = MAXIMUM INFECTION EXPECTED IN STANDS AFTER THINNING. IDEAL
C           FOR STANDS NOT ALREADY BEYOND DMR OF 3.0.
C      DSTY = LOWEST VALUE OF DLEV USED IN A TEST.
C      HTSO = TREE HEIGHT BEFORE THINNING.
C      HTST = TREE HEIGHT AFTER THINNING.
C      INVL(I) = NEW CUTTING CYCLE AFTER REGENERATION CUT I.
C      JCYCL = INTERVAL BETWEEN INTERMEDIATE CUTS.
C      JSBD = SUM OF BOARD FEET FROM ALL CUTS WITH YIELD OF COMBF OR
C           LARGER.
C      JSMC = SUM OF MERCH. CU. FT. FROM ALL CUTS WITH YIELD OF COMCU
C           OR LARGER.
C      JSTF = SUM OF TOTAL CU. FT. FROM ALL CUTS.
C      KSTEP = INDICATOR WITH VALUE OF ONE IF CURRENT THINNING IS FROM
C           BELOW AND TWO IF CURRENT THINNING IS FROM ABOVE.
C      KTR  = INDICATOR WITH VALUE GREATER THAN ZERO IF A SCHEDULED
C           THINNING HAS BEEN SKIPPED BECAUSE MISTLETOE INDEX IS TOO HIGH
C           OR BECAUSE STAND IS ALREADY TO SPECIFIED STOCKING.
C      MIX = NUMBER OF STOCKING LEVELS EXAMINED PER TEST.
C      NFLAG = INDICATOR WITH VALUE GREATER THAN ZERO IF A THINNING FROM
C           ABOVE HAS BEEN MADE AT ANY TIME.
C      NTSTS = NUMBER OF TESTS PER BATCH.
C      OUT = PERCENT MORTALITY IN HEALTHY STANDS.
C      PCT  = PERIODIC HEIGHT INCREASE IN INFESTED STAND, AS A PERCENTAGE
C           OF THE INCREASE IN COMPARABLE HEALTHY STANDS.
C      PRET = PERCENTAGE OF TREES RETAINED AFTER THINNING.
C      REDT = PERCENTAGE REDUCTION IN NUMBER OF TREES WHEN DMR IS
C           REDUCED TO DMRT BY THINNING.
C      REGN(I) = STAND AGE WHEN REGENERATION CUT I OCCURS.
C      RINT = NUMBER OF YEARS FOR WHICH A SINGLE PROJECTION IS MADE.
C      ROTA = FINAL AGE IN YIELD TABLE.
C      SITE = SITE INDEX.
C      START = STAND AGE AT TIME OF INITIAL INFECTION.
C      THM  = PERIODIC D.B.H. INCREASE IN INFESTED STAND, AS A PERCENTAGE
C           OF THE INCREASE IN COMPARABLE HEALTHY STANDS.
C      THIN = GROWING STOCK LEVEL FOR INITIAL THINNING.
C      TOTC = TOTAL CUBIC FEET CUT PER ACRE.
C      TOTO = TOTAL CUBIC FEET PER ACRE BEFORE THINNING.
C      TOTT = TOTAL CUBIC FEET PER ACRE AFTER THINNING.
C      VLVE(I)  = PERCENT OF PREVIOUS FLEV TO BE LEFT AT REGN(I), ENTERED
C           AS A DECIMAL.
C
      COMMON BA,BAST,DBHO,DBHT,DENO,DMR,DMRT,FCTR,PRET,PROD,REST,VOM
      DIMENSION VAR(11),TEMP(2),INVL(3),REGN(3),VLVE(3)
C
      DO 1 I=1,11
    1 VAR(I) = 0.0
C
C  READ NUMBER OF TESTS PER BATCH FROM CARD TYPE ONE.
C
      READ (5,5) NTSTS
    5 FORMAT (I4)
      IF(NTSTS .LE. 0) GO TO 470
C
C  READ MINIMUM COMMERCIAL  UTS FOR COMPUTATION OF COLUMN TITALS FROM
C  CARD TYPE TWO.
C
      READ (5,10) COMCU,COMBF
   10 FORMAT (I6,F3.1)
      VAR(9)  = COMBF
      VAR(10) = COMCU
C
C  EXECUTE PROGRAM ONCE FOR EACH SET OF INITIAL VALUES OF INTEREST.
C
      DO 460 I=1,NTSTS
      ITEM = 5
C
C  READ CUTTING INTERVAL AND LEVELS PER TEST FROM CARD TYPE THREE.
C
      READ (5,15) JCYCL,MIX
   15 FORMAT (I2,I4)
      IF(JCYCL .LE. 0 .OR. MIX .LE. 0) GO TO 470
      JTEM = JCYCL
C
C  READ INITIAL STAND VALUES FROM CARD TYPE FOUR.
C
      READ (5,10) AGEO,DBHO,DENO,DSTY,RINT,SITE,THIN,START
      VAR(1) = AGEO
      VAR(2) = DBHO
      VAR(3) = DENO
      VAR(4) = DSTY
      VAR(5) = RINT
      VAR(6) = SITE
      VAR(7) = THIN
      VAR(8) = START
C
C  READ SILVICULTURAL CONTROLS FROM CARD TYPE FIVE.
C
      READ (5,10)REGN(1),VLVE(1),INVL(1),REGN(2),VLVE(2),INVL(2),REGN(3)
      VAR(11) = REGN(1)
      DO 20 I=1,11
      IF(VAR(I) .LE. 0.0) GO TO 470
   20 CONTINUE
      DLEV = 0.0
      DO 35 NA=1,3
      L = 4 - NA
      IF(REGN(L) .EQ. 0.0) GO TO 35
      ROTA = REGN(L)
      GO TO 40
   35 CONTINUE
C
C  PROVIDE FOR SEVERAL GROWING STOCK LEVELS PER TEST.
C
   40 DO 460 M=1,MIX
      A = M
      ADJHT = 0.0
      BDFO = 0.0
      BDFT = 0.0
      CFMO = 0.0
      CFMT = 0.0
      DMR  = 0.0
      DMRT = 0.0
      HTGRO = 0.0
      JSBD = 0
      JSMC = 0
      JSTF = 0
      KSTEP = 1
      KTR = 0
      NFLAG = 0
      TIME = 0.0
      DLEV = (DSTY + (A * 10.0)) - 10.0
      FAST = DENO * 0.0054542 * DBHO * DBHO
C
C  COMPUTE CURRENT DWARF MISTLETOE RATING, UNTHINNED STANDS.
C
      TIME = AGEO - START
      IF(TIME .LE. 0.0) GO TO 45
      DMR = 0.06533 * TIME + 0.03676 * SITE - 1.4486
      IF(DMR .LT. 0.0) DMR = 0.0
      IF(DMR .GT. 6.0) DMR = 6.0
C
C  OBTAIN AVERAGE HEIGHT AND VOLUMES PER ACRE.
C
   45 IF(AGEO .GT. 55.0) GO TO 50
      HTSO = 0.01441 * AGEO * SITE - 0.12182 * AGEO - 1.50953
      GO TO 55
   50 HTSO = 0.59947 - 61.5019 / AGEO + 0.80522 * ALOG10(SITE) + 20.5252
     1/R * ALOG10(SITE) / AGEO
      HTSO = 10.0 ** HTSO
   55 PCT = 1.073 - 0.0367 * DMR
      IF(PCT .GT. 1.0) PCT = 1.0
      HTSO = HTSO * PCT
C
C  COMPUTE TOTAL CU. FT. AND CONVERT TO OTHER UNITS.
C
      D2H = DBHO * DBHO * HTSO
      IF(D2H .GT. 5000.0) GO TO 60
      TOTO = 10.53313 + 0.00033 * BASO + 0.00179 * D2H * DENO
      GO TO 65
   60 TOTO = 10.00237 * BASO + 0.00211 * D2H - 1.09356) * DENO
   65 IF(DBHO .LT. 5.0) GO TO 70
      VOM = DBHO
      BA = BASO
      CALL SWVOL
      BDFO = TOTO * PROD
      CFMO = TOTO * FCTR
   70 REST = THIN
C
C  ENTER LOOP FOR REMAINING COMPUTATIONS AND PRINTOUT.
C
      DO 455 K=1,100
C
C  CHANGE STANDARDS IF A REGENERATION CUT IS DUE.
C
   80 IF(AGEO .GE. ROTA) GO TO 165
      IF(AGEO .LT. REGN(1)) GO TO 108
      IF(AGEO .NE. REGN(1)) GO TO 95
      DLEV = DLEV * VLVE(1)
      REST = DLEV
      JCYCL = INVL(1)
      GO TO 105
   95 IF(AGEO .NE. REGN(2)) GO TO 100
      DLEV = DLEV * VLVE(2)
      REST = DLEV
```

```
   JCYCL = INVEL(2)
   GO TO 105
30 IF(AGE .GE. REGEN(3)) GO TO 165
   DLEV = DLEV * VLEV(3)
   REST = DLEV
   JCYCL = INVEL(3)

CREASE D.B.H. BY THINNING AND COMP TE POST THINNIN  ,****.

35 IF(AGE .EQ. REGEN(1) .OR. AGE .EQ. REGEN(2)) G  TO 1 4
38 IF(DMR .LT. 3.01 GO TO 110
   BAST = BASO
   DBHT = DBHO
   DMRT = DMR
   HTST = HTSO
   KTK = 1
   GO TO 150
40 IF(DMR .EQ. 0.0) GO TO 120
   IF(IFLAG .GT. 0) GO TO 115
   DMRT = 0.25 * DBHO - 0.50
   IF(DMRT .LT. 0.01) DMRT = 0.0
   IF(DMRT .GE. DMR) GO TO 115
   CALL SWCUT2
   NFLA, = 1
   KSTEP = 2
   GO TO 125
45 CALL SWCUT3
   KSTEP = 1
   DMRT = DMR + 0.0277 * PRET - 2.77
   GO TO 125
50 DMRT = DMR
   CALL SWCUT1
   KSTEP = 1
   GO TO 125
55 CALL SWC T1
   KSTEP = 1
   DMRT = DMR + 0.0277 * PRET - 2.77
   IF(DMRT .GT. 6.01 DMRT = 6.0
60 IF(BAST .LT. BAST) GO TO 135
   BAST = BASO
   DBHT = DBHO
   DMRT = DMR
   HTST = HTSO
   KTK = 1
   GO TO 150

APUTE HEIGHT AND VOLUMES AFTER THINNING.

   GO TO (145,140),KSTEP
   ADDHT = 7.66833 - 1.82286 * ALOG10(PRET)
   GO TO 145
   ADDHT = 3.4177 * ALOG10(PRET) - 5.68883 / BAST - 7.2  1
   HTCUM = HTCUM + ADDHT
   HTST = HTSO + ADDHT
   JDENT = (BAST / (0.0054542 * DBHT * DBHT)) + 0.5
   DENT = JDENT
   BAST = 0.0054542 * DBHT * DBHT * DENT
   D2H = DBHT * DBHT * HTST
   IF(D2H .GT. 5000.0) GO TO 155
   TOTT = (0.53313 + 0.00033 * BAST + 0.00179 * D2HT * BAST
   GO TO 160
   TOTT = 10.66237 * BAST + 0.00211 * D2H - 1.67956) * FACT

ONVERT TOTAL CU. FT. TO OTHER UNITS.

   IF(DBHT .LT. 5.0) GO TO 165
   VDM = DBHT
   BA = BAST
   CALL SWVOL
   BDFT = TCFT * PRIO
   CFMT = TOTT * FCTR

NGE MODE AND ROUND OFF FOR PRINTING.

   JAGE = AGE
   JSITE = SITE
   JDENO = DENO + 0.5
   JHTSO = HTSO + 0.5
   JTOTC = (TCTO * .1) + 0.5
   JTOTO = JTOTO * 10
   JBAS. = BASO + 0.5
   JCFMO = ((FMO * 0.1) + 0.5
   JCFMO = JCFMO * 10
   JBDFO = (BDFO * 0.01) + 0.5
   JBDFO = JBDFO * 100
   JHTST = HTST + 0.5
   JTOTT = (TOTT * 0.1) + 0.5
   JTOTT = JTOTT * 10
   JCFMT = (CFMT * 0.1) + 0.5
   JCFMT = JCFMT * 10
   IF(JCFMT .GT. JCFMO) JCFMO = JCFMT
   JBDFT = (BDFT * 0.01) + 0.5
   JBDFT = JBDFT * 100
   IF(JBDFT .GT. JBDFO) JBDFO = JBDFT
   JBAST = BAST + 0.5
   JDENC = JDENO - JDENT
   JBASC = JBASO - JBAST
   JTOTC = JTOTO - JTOTT
   JCFMC = JCFMO - JCFMT
   IF(JCFMC .LE. 0) JCFMC = 0
   JBDFC = JBDFO - JBDFT
   IF(JBDFC .LE. 0) JBDFC = 0

S PERIODIC CUTS FOR LAST LINE OF YIELD TABLE.

   IF(AGE .GE. ROTA) GO TO 190
   JSTE = JSTE + JTOTC
   CFMC = JCFMC
   IF(CFMC .LT. COMC(1) GO TO 170
   JSMC = JSMC + JCFMC
1  BDFC = JBDFC
   IF(BDFC .LT. COMBF) GO TO 180
   JSBD = JSBD + JBDFC

W F HEADINGS FOR YIELD TABLE.

1  IF(K .GE. 2) GO TO 220
   WRITE (6,175) JSITE,THIN,LEV
1  FORMAT (1H1,///,39X,53HYIELDS PE- ACRE OF EVEN AND  AGED  STA
   EROSA PINE/1H ,57X,11HSITE INDEX ,I3/1H ,38X,20HTHINNING  TYP  ,I1/1
   2- INITIAL- ,F5.0,2X,12HSQ.RDS.BASE,DENT- ,F5.0)
   WRITE (6,200)
2  FORMAT (1H0,25X,39HS.FIRE STAND BEFORE AN  AFTER THINNI  ,2X,
   ERIODIC INTERMEDIATE CUTS)
   WRITE (6,205)
2  FORMAT (1H0,9X,5HSTAND,10X,5HBASAL,4X,7HAVERAGE ,3,' A  A  ,2X,
   T.TAL,3X,9HMERCHANT-,1X,9HSAWTIMBER,,4X,5HBASAL ,4X,  TAL ,3X,9HM
   'CHANT-,3X,9HSAWTIMBER)
```

```
      WRITE (6,210)
210   FORMAT (1H ,2X,3HAGE,3X,5HTREES,3X,5HTREES,3X,5HDIAM.,3X,
     1,5HYRS.,3X,5HPER A,3X,5HPER A,3X,5HDIAM.,3X,5HPER A,3X,
     2,5HCU.FT.,3X,5HBD.FT.,3X,11HPER ACRE,/,3X,3HYRS,4X,5HACRE,3X,
     3,5HACRE,3X,5HBH.D.,3X,5HCU.FT.,3X,5HBD.FT.,3X,5HCU.FT.,3X,
     4,5HBD.FT.,/,3X,3H(0),3X,5H(1),3X,5H(2),3X,5H(3),3X,5H(4),3X,
     5,5H(5),3X,5H(6),3X,5H(7),3X,5H(8),3X,5H(9),3X,5H(10),3X,5H(11)
C
C  WRITE IN  I.ITIAL , OF STAND ITE, /I MGT, ET .
C
      IF(AGE .GE. ROTA) GO TO 230
      WRITE (6,215) JAGE,JTOTO,JBAS.,JCFMO,JBDFO,JHTST,JTOTT,JCFMT,JBDFT
215   FORMAT (1H0,3X,I3,3X,I5,3X,I5,3X,I5,3X,I5,3X,I5,3X,I5,3X,I5,3X,I5,
     1,3X,I5,3X,I4,3X,I5,3X,I5,3X,I5)
      IF(AGE .EQ. ROTA) GO TO 240
      WRITE (6,225) JAGE,JTOTC,JBASC,JCFMC,JBDFC,JHTST,JTOTT,JCFMT,JBDFT
225   FORMAT (1H ,3X,I3,3X,I5,3X,I5,3X,I5,3X,I5,3X,I5,3X,I5,3X,I5,3X,I5,
     1,3X,I5,3X,I4,3X,I5,3X,I5,3X,I5)
C
C  COMPUTE VALUES FOR EACH CYCLE . THEN AG  RE ITE .
C
      IAINT = MINT
      IR = JCYCL / IMINT
      I = 345 * I.IR
      AGE = AGE + REST
      IF(AGE .LT. ROTA) GO T  ***
C
C  COMPUTE CURRENT  WAGE MISTLETOE RATING.
C
      TIME = AGE - START
      IF(DMR .LT. 3.0) GO T  ***
      IF(TIME .LE. 5.0) GO TO ***
      DMR = 0.0033 * TIME + 0.0016 * SITE - 1.4484
      GO TO ***
250   IF(DMRT .LT. 1.0) GO T  ***
      DMR = DMR + 0.005 * MINT
      GO TO 260
255   DMR = DMRT + (3. 3 + 0.338 * DMRT) * RIAT
      IF(I .LE. 2) GO TO 260
      DMR = DMR + (0.05 * MINT
260   IF(DMR .LT. 0.0) DMR = 0.
      IF(DMR ...L. 6.0) DMR = 6.
C
C COMPUTE NEW D.B.H. AFTER  THINNING AN  REGN  ** IS  .I ***.
C
      DBH = 1.0047 * DBHT + 0.0  * (EE 11.5*A*BA/ALOG10(A 1***.**1
      IF(DMRT .LE. 4.5) GO T  ***
      TEM = (0.05 - .DMRT. * 11.  ( 1.15A * DMRT ***.147 )
      DBH = DBH + TEM
      IF(DBH .GE. DBHT) DBH = DBHT
      DBHO = DBHO * 0.1
      IF (DBH .LT. 1.0) DBH = 1.0
      BA = 0.0054542 * 4.4627. * DMRT  1.*A374 * ITI * ***.**** * ****.
     1DBH**2)
      TEM = TEM * 0.01
      IF(A .LT. 0.0) BA = 0.
      ZA 0.0 = 1.0
      IF(DMRT .GE. 1.5) G  T .75
      DIF = 0.3247 + 0.1124 * DMRT + 3.3128 * DMT * DMT + .
   11 * BA T * BAST + .  * DMRT * BA T
      IF(DIF .LT. 0.0) DIF = 0.
275   IF(DIF .LT. 0.0) DIF = DIF
      JDENC = JDENT * 11.0 - (DENT) + 0.5
      JDENC = JDENC
      BA = (0.0 * 10.0054542 * DMRT * DBHT)
C
C  BEGIN AVERAGE HEIGHT AND VOLUME, PER ACRE.
C
      DO 300 I=1,2
      LUB = J
      GO TO (***),J
      DO 290 I = 1,
      IF(I .EQ. 1) GO TO 280
      YAR = BASO
      GO TO 285
280   YAR = BAST
285   IF(YAR .LT. 55.0) G  T  295
      TEMH(I) = .0*1441 * YAR * SITE  .1*1A1 * YAR - 1.5***
      GO TO 290
295   TEMH(I) = 0.53947 - A1.0 (I / YAR + 0.00522 * A  ***.** * ***.
     1253* * A  ***.1111 / YA
      TEMH(I) = 10.0 ** TEMH I
290   CONTINUE
      HGT = 120 - 0.**** * HGT * DMRT * DMRT
      CMAI = (TEMH(1) - TEMH(2)) * FCT
      HT.I = HGT I + CMAI
C
C COMPUTE TOTAL CU. FT. AND CONVERT TO OTHER UNITS.
C
      TOT = DENT * DBHT * HTS
      IF(DMR .LT. 3.0) G  T  ***
      TOTT = 0.53313 + 0.00033 * BAST + 0.00179 * D2HT * BAST
      GO TO ***
295   TOTT = 10.66237 * BAST + 0.00211 * D2H - 1.67956) * FACT
      IF(DBHT .LT. 5.0) G  T  ***
      VDM = DBHT
      BA = BASO
      CALL SWVOL
      BDFT = TCFT * PRIO
      CFMT = TOTT * FCTR
C
C  I.IT IL BEGIN ERATI  OUT IT  ***.
C
      DO 315 K=1,4
      IF(AGE .GE. REGEN(K)) GO TO ***
315   CONTINUE
C
C CHANGE MODE AN  ROUND OFF FOR PRINTING.
C
      JAGE = AGE
      JSITE = SITE
      JDENO = DENO + 0.5
      JHTSO = HTSO + 0.5
      JTOTC = TCTO * .1
      JTOTO = JTOTO * 10
      JBAS. = BASO
      JCFMO = FMO * 0.1
      JCFMO = JCFMO * 10
      JBDFO = BDFO * 0.01
      JBDFO = JBDFO * 100
      JHTST = HTST + 0.5
      JTOTT = TOTT * 0.1
      JTOTT = JTOTT * 10
      JCFMT = CFMT * 0.1
      JCFMT = JCFMT * 10
      JBDFT = BDFT * 0.01
      JBDFT = JBDFT * 100
C
C  WRITE  ***.** * ** ** ***** ** ***. ** * ***.
C
      WRITE (6,***) JAGE,JTOTO,JBAS.,JCFMO,JBDFO,JHTST,JTOTT,JCFMT,JBDFT
      DMRT = DMR
```

```
      RETURN
  665 CONTINUE
C
C  GO BACK TO START LOOP AGAIN FOR NEXT THINNING.
C
  666 RETURN
  667 CONTINUE

C  AT FINAL CYCLE, GO TO TOTAL YIELDS AND WRITE TOTAL YIELDS.

      IF (ITEM .EQ. NTHIN) GO TO 675
      ITEM = ITEM + 1
      IF (ITEM .LT. IOMEG) GO TO 675
      ITEM = ITEM + IOMEG
  675 DO 680 JB=1,2
      IF (ITEM .LT. IOMEG) GO TO 680
      ITEM = ITEM - IOMEG
  680 CONTINUE
      WRITE (6,690) JSTR,JSMC,ISM
  690 FORMAT (1H0,7X,7HSTRATA,6X,7HSAMPLE,6X,14,8X,14,8X,14)
      WRITE (6,700) CUMCU,CUMBF
  700 FORMAT (1H0,7X,11HTOTAL YIELDS,2X,F14.4,8X,F14.4,8X,15)
      WRITE (6,705) CUMCU,CUMBF
  705 FORMAT (1H0,7X,11HTOTAL YIELDS,2X,F14.4,8X,F14.4,8X,15)
      WRITE (6,710)
  710 FORMAT (1H0,7X,46HMINIMUM DBH FOR INCLUSION IN TOTAL YIELDS--
     1 F4.1,1H0,5X,9HCU. FEET,4X,F7.1,11H BOARD FEET)
      IF (START .EQ. 0) GO TO 735
      WRITE (6,720) START,CMV,POTA
  720 FORMAT (1H0,15X,41HDWARF MISTLETOE INFECTION STARTED AT AGE ,F4.0,
     1 1H0 AND RATING WAS ,F5.1,9H AT AGE ,F4.0)
      GO TO 745
  735 WRITE (6,740) POTA
  740 FORMAT (1H0,10X,43HDWARF MISTLETOE INFECTION DID NOT OCCUR DURING
     1 THE ROTATION OF ,F4.0,7H YEARS.)
  745 IF (KTR .EQ. 0) GO TO 425
      WRITE (6,420)
  420 FORMAT (1H0,10X,52HNOTE THAT NOT ALL SCHEDULED THINNINGS WERE POS
     1IBLE.)
  425 WRITE (6,430)
  430 FORMAT (1H0,10X,68HMERCH. CU. FT. - TREES 6.0 INCHES D.B.H. AND LA
     1RGER TO 4.0-INCH TOP.)
      WRITE (6,435)
  435 FORMAT (1H0,10X,68HBD. FT. - TREES 10.0 INCHES D.B.H. AND LARGER T
     1O VARIABLE TOP LIMIT.)
C
C  PREPARE FOR NEXT TABLE OF THE TEST.
C
      AGE = VAR(1)
      DBHQ = VAR(2)
      DEN = VAR(3)
      JCYCL = JTEM
  460 CONTINUE
      GO TO 500
C
C  PROGRAM CONTROL GOES HERE IF ANY UNWANTED ZEROS IN DATA DECK.

  470 WRITE (6,480)
  480 FORMAT (1H1,///,10X,64HEXECUTION STOPPED BECAUSE OF NEGATIVE OR ZE
     1RO ITEM ON DATA CARD.)
  560 CALL EXIT
      END
```

```
      SUBROUTINE SWVOL
C
C  TO CONVERT TOTAL CU. FT. TO MERCH. CU. FT. AND TO BD. FT.
C
      COMMON BA,BAST,DBHQ,DBHT,DENQ,DMR,DMRT,FCTR,PRET,PROD,REST,VDM
C
      FCTR = 0.0
      PROD = 0.0
      IF(VDM .LT. 5.0) GO TO 10
C
C  OBTAIN CONVERSION FACTORS FOR MERCH. CU. FT. - VOLUMES TO 4.0-INCH TOP
C  IN TREES 6.0 INCHES D.B.H. AND LARGER.
C
      IF(VDM .GT. 6.5) GO TO 2
      FCTR = 0.25222 * VDM - 1.01119
      GO TO 6
    2 IF(VDM .GT. 10.0) GO TO 4
      FCTR = 3.02485 - 0.09957 * VDM - 11.35814 / VDM
      GO TO 6
    4 FCTR = 1.03936 - 1.41334 / VDM
    6 IF(VDM .LT. 8.0) GO TO 10
C
C  OBTAIN CONVERSION FACTORS FOR BD. FT. - VOLUMES TO VARIABLE TOP IN
C  TREES 10.0 INCHES D.B.H. AND LARGER.
C
      IF(VDM .GT. 11.5) GO TO 8
      PROD = 0.0028 * BA + 0.04355 * VDM * VDM - 2.7832
      GO TO 10
    8 PROD = 0.83943 + 0.20531 * VDM
   10 RETURN
      END
```

```
      SUBROUTINE SWCUT1
C
C  TO ESTIMATE INCREASE IN AVERAGE D.B.H. DUE TO THINNING SOUTHWESTERN
C  PONDEROSA PINE IF DWARF MISTLETOE RATING EQUALS ZERO.
C
      COMMON BA,BAST,DBHQ,DBHT,DENQ,DMR,DMRT,FCTR,PRET,PROD,REST,VDM
C
      IF(DBHQ .LT. 9.5) GO TO 30
C
C  COMPUTE D.B.H. IF DBHQ IS LARGE ENOUGH FOR BASAL AREA TO REMAIN CONSTANT.
C
      PRET = 100.0
      DO 21 KJ=1,100
      IF(PRET .LT. 50.0) GO TO 5
      DBHE = 0.73365 + 1.02008 * DBHQ - 0.01107 * (PRET - 50.0) - 0.0001
     14 * (PRET - 50.0) * (PRET - 50.0)
      GO TO 11
    5 PDBHE = 0.49401 + 0.71890 * ALOG10(DBHQ) - 0.22530 * ALOG10(PRET)
     1 + 0.12616 * ALOG10(DBHQ) * ALOG10(PRET)
      DBHE = 10.0 ** PDBHE
   11 IDBHE = DBHE * 10.0 + 0.5
      DBHE = IDBHE
      DBHE = DBHE * 0.1
      DENE = DENQ * PRET * 0.01
      NDENE = DENE + 0.5
      DENE = NDENE
      BASE = 0.0054542 * DBHE * DBHE * DENE
      NBASE = BASE * 10.0 + 0.5
      BASE = NBASE
      BASE = BASE * 0.1
      TMPY = 0.0054542 * DBHE * DBHE
      TEM = BASE - REST
      IF(ITEM .LL. TMPY) GO TO 20
      IF(ITEM .LT. 4.0) GO TO 20
      PRET = PRET - 1.0
      GO TO 21
   20 PRET = PRET - 0.3
   21 CONTINUE
      GO TO 70
C
C  COMPUTE D.B.H. IF BASAL AREA INCREASES WITH D.B.H.
C
   30 PRET = 40.0
      IF(DBHQ .GT. 7.01) PRET = 70.0
      DO 65 J=1,100
      IF(PRET .GE. 50.0) GO TO 40
      PDBHE = 0.49401 + 0.71890 * ALOG10(DBHQ) - 0.22530 * ALOG10(PRET)
     1 + 0.12616 * ALOG10(DBHQ) * ALOG10(PRET)
      DBHE = 10.0 ** PDBHE
      GO TO 45
   40 DBHE = 0.73365 + 1.02008 * DBHQ - 0.01107 * (PRET - 50.0) - 0.0001
     14 * (PRET - 50.0) * (PRET - 50.0)
   45 IDBHE = DBHE * 10.0 + 0.5
      DBHE = IDBHE
      DBHE = DBHE * 0.1
      DENE = DENQ * (PRET * 0.01)
      NDENE = DENE + 0.5
      DENE = NDENE
      BASE = 0.0054542 * DBHE * DBHE * DENE
      NBASE = BASE * 10.0 + 0.5
      BASE = NBASE
      BASE = BASE * 0.1
      BREAK = 49.9 * REST / 80.0
      IF(BASE .GT. BREAK) GO TO 50
      DBHP = (80.0 / REST) * (0.08682 * BASE) + 0.94636
      GO TO 52
   50 BUST = 66.2 * (REST / 80.0)
      IF(BASE .GT. BUST) GO TO 51
      DBHP = (80.0 / REST) * (0.10938 * BASE) - 0.17858
      GO TO 52
   51 TMPY = BASE * (80.0 / REST)
      TEM = TMPY * TMPY
      DBHP = 13.04740 * TMPY - 0.26673 * TEM + 0.0012539 * TEM * TMPY
     1 - 448.76833
      IF(TMPY .GT. 80.0) DBHP = DBHQ + 0.8
   52 IDBHP = DBHP * 10.0 + 0.5
      DBHP = IDBHP
      DBHP = DBHP * 0.1
      IF(DBHP - DBHE) 60,70,61
   60 PRET = PRET * 1.02
      GO TO 65
   61 PRET = PRET * 0.98
   65 CONTINUE
   70 DBHT = DBHE
C
C  COMPUTE POST-THINNING BASAL AREA.
C
      IF(DBHT .GT. 5.0) GO TO 75
      SQFT = 11.58495 * DBHT - 11.09724
      GO TO 76
   75 IF(DBHT .GE. 10.0) GO TO 77
      TEM = DBHT * DBHT
      SQFT = 7.76226 * DBHT +0.85289 * TEM -0.07952 * TEM * DBHT-3.45624
   76 BAST = (REST / 80.0) * SQFT
      GO TO 80
   77 BAST = REST
   80 RETURN
      END
```

```
      SUBROUTINE SWCUT2
C
C  TO ESTIMATE INCREASE IN AVERAGE D.B.H. DUE TO THINNING SOUTHWESTERN
C  PONDEROSA PINE IF DWARF MISTLETOE RATING DETERMINES THE STANDARDS.
C
      COMMON BA,BAST,DBHQ,DBHT,DENQ,DMR,DMRT,FCTR,PRET,PROD,REST,VDM
C
C  COMPUTE STAND DENSITY AFTER A THINNING THAT REDUCES THE INDEX.
C
      IF(DMR .LT. 2.0) GO TO 5
      REDT = 77.5 - 8.5 * DBHQ + 10.0 * DMR
      GO TO 10
    5 REDT = 15.5 - 8.5 * DBHQ + 41.0 * DMR
   10 PRET = 100.0 - REDT
      DENT = DENQ * (PRET * 0.01)
      IDENT = DENT + 0.5
      DENT = IDENT
C
C  COMPUTE D.B.H. AFTER THINNING TO DESIRED DENSITY.
C
      IF(PRET .LT. 50.0) GO TO 15
      DBHT = 0.98543 * DBHQ + 0.00807 * (PRET - 50.0) + 0.00025 * (PRET
     1 - 50.0) * (PRET - 50.0) - 0.91172
      GO TO 20
   15 DBHT = 0.51618 * ALOG10(PRET) + 1.69219 * ALOG10(DBHQ) - 0.34768 *
     1ALOG10(PRET) * ALOG10(DBHQ) - 1.03421
      DBHT = 10.0 ** DBHT
   20 IDBHT = DBHT * 10.0 + 0.5
      DBHT = IDBHT
      DBHT = DBHT * 0.1
      BAST = 0.0054542 * DBHT * DBHT * DENT
      RETURN
      END
```

```
      SUBROUTINE SWCUT4
C
C TO ESTIMATE INCREASE IN AVERAGE D.B.H. DUE TO  THINNING FROM ABOVE IN
C WARE MISTLETOE RATING IS GREATER THAN ZERO.
C
      COMMON BA,RASI,DBHQ,DBHT,DENS,DMR,DMRT,ECTP,PRET,PROP,T,TYPE
      IF(DBHT .LT. 9.5) GO TO 40
C
C COMPUTE D.B.H. IF DBHQ IS LARGE ENOUGH FOR BASAL AREA TO REMAIN CONSTANT.
C
      PRET = 130.0
      DO 21 K=1,100
      IF(PRET .LT. 50.0) GO TO 5
      DBHQ = 0.73365 + 1.02809 * DBHQ - 0.01167 * (PRET - 50.0) + 0.0001
     14 * (PRET - 50.0)**2 + (PRET - 50.0)
      GO TO 11
    5 PDBHE = -0.49401 + 0.71831 * ALOG10(DBHQ) - 0.2253 * ALOG10(T)
     1 + 0.12616 * ALOG10(DBHQ) * ALOG10(PRET)
      DBHE = 10.0 ** PDBHE
   11 TEM = DBHE - DBHQ
      DBHE = DBHQ + TEM * 0.5
      IF(DBHE - DBHT * 1.2) 12,12,13
   12 DBHE = DBHT
   13 DBHE = DBHE * 0.1
      DENE = DENS * PRET * 0.01
      NDENE = DENE * 0.5
      DENE = NDENE
      BASE = 0.3054542 * DBHE * DBHE * DENE
      NBASE = BASE * 10.0 * 0.5
      BASE = NBASE
      BASE = BASE * 0.1
      TMPY = 0.3054542 * DBHE * DBHE
      TEM = BASE - REST
      IF(TEM .LE. TMPY) GO TO 70
      IF(TEM .LT. 4.0) GO TO 20
      PRET = PRET - 1.0
      GO TO 21
   20 PRET = PRET - 0.1
   21 CONTINUE
      GO TO 70
C
C COMPUTE D.B.H. IF BASAL AREA INCREASES WITH D.B.H.
C
   40 PRET = 40.0
      IF(DBHQ .GT. 7.01 PRET = 70.0
      DO 65 J=1,100
      IF(PRET .GE. 50.0) GO TO 40
      PDBHE = -0.49401 + 0.71831 * ALOG10(DBHQ) - 0.22516 * ALOG10(T)
     1 + 0.12616 * ALOG10(DBHQ) * ALOG10(PRET)
      DBHE = 10.0 ** PDBHE
      GO TO 45
   40 PDBHE = -0.49401 + 0.71831 * ALOG10(DBHQ) - 0.22516 * ALOG10(T)
     1 + 0.12616 * ALOG10(DBHQ) * ALOG10(PRET + 50.0)
   45 TEM = DBHE - DBHQ
      TEMP = TEM + TEM * 0.5
      IF(TEMP - TEM * 1.2) 46,46,47
   46 TEM = TEMP
   47 IF(DBHE - DBHT * .1
      ESP = -0.0025 * (PRET + 50.0)
      DENE = DENS * EXP
      NDENE = DENE
      BASE = 0.3054542 * DBHE * DBHE * ESP
      NBASE = BASE * 10.0 * 0.5
      BASE = NBASE
      BASE = BASE * 0.1
      IF(BASE .LE. BREAK) GO TO 50
      DBHE = DBHE / RATIO + 0.1 * (BASE - BREAK)
      GO TO 52
   50 DBHE = DBHE / RATIO
   52 IF(BASE .LT. 0.1) GO TO 51
      DBHE = DBHE / RATIO + 0.1 * (BASE - 0.1)
      GO TO 52
   51 TMPY = 0.3... * DBHE... / RATIO
      TEM = TMPY * TMPY
      DBHE = 1.204740 * TMPY - 0.22273 * TEM + 0.1... * TEM * TEM
     1 - 0.0468,76*TEM
      IF(TMPY .GT. 40.0) DBHE = DBHQ + 0.2
   52 IF(DBHE - DBHQ * 1.2) 53,53
      DBHE = DBHQ * 1.2
   53 IF(DBHE - DBHT) 54,54,55
   54 PRET = PRET + 1.0
      GO TO 65
   55 PRET = PRET * 0.98
   65 CONTINUE
   70 DBHT = DBHE
C
C COMPUTE NEW TREE THINNED BASAL AREA.
C
      IF(DBHT .GT. 9.01) GO TO 75
      PRET = 11.59435 * DBHT - 11.09724
      GO TO 77
   75 IF(DBHT .GE. 16.0) GO TO 77
      TEM = DBHT * DBHT
      PRET = 7.7227 * DBHT + 0.15212 * TEM + 0.... * TEM * TEM * TEM
   76 BAST = (RASI / 43.... * PRET
      GO TO 80
   77 BAST = RASI
   80 RETURN
      END
```

APPENDIX 2
Output of Sample Problem

YIELDS PER ACRE OF EVEN-AGED STANDS OF PONDEROSA PINE
SITE INDEX 70
THINNING INTENSITY- INITIAL- 100. SUBSEQUENT- 80.

	ENTIRE STAND BEFORE AND AFTER THINNING							PERIODIC INTERMEDIATE CUTS				
STAND AGE (YEARS)	TREES NO.	BASAL AREA SQ.FT.	AVERAGE D.B.H. IN.	AVERAGE HEIGHT FT.	TOTAL VOLUME CU.FT.	MERCHANT-ABLE VOLUME CU.FT.	SAWTIMBER VOLUME BD.FT.	TREES NO.	BASAL AREA SQ.FT.	TOTAL VOLUME CU.FT.	MERCHANT-ABLE VOLUME CU.FT.	SAWTIMBER VOLUME BD.FT.
30	950	119	4.8	25	1530	360	0					
30	373	68	5.8	27	810	360	0	577	51	720	0	0
40	370	96	6.9	36	1330	920	0					
50	365	121	7.8	44	1970	1560	800					
50	188	76	8.6	45	1230	1040	800	177	45	740	520	0
60	187	96	9.7	52	1730	1530	2700					
70	186	114	10.6	58	2420	2190	5900					
70	113	80	11.4	59	1730	1580	5400	73	34	690	610	500
80	113	96	12.5	65	2320	2150	7900					
90	113	112	13.5	70	2930	2740	10600					
90	72	80	14.3	70	2120	2000	8000	41	32	810	740	2600
100	72	93	15.4	75	2620	2490	10500					
110	72	106	16.4	78	3130	2990	13200					
110	22	39	18.1	80	1190	1150	5400	50	67	1940	1840	7800
120	22	47	19.7	83	1480	1430	7200					
130	22	54	21.2	86	1770	1720	9200					
						TOTAL YIELDS				6670	5430	17600

MINIMUM CUTS FOR INCLUSION IN TOTAL YIELDS-- 320. CUBIC FEET AND 1500. BOARD FEET

DWARF MISTLETOE INFECTION DID NOT OCCUR DURING THE ROTATION OF 130. YEARS.

MERCH. CU. FT. - TREES 6.0 INCHES D.B.H. AND LARGER TO 4.0-INCH TOP.

BD. FT. - TREES 10.0 INCHES D.B.H. AND LARGER TO VARIABLE TOP LIMIT.

YIELDS PER ACRE OF EVEN-AGED STANDS OF PONDEROSA PINE
SITE INDEX 70
THINNING INTENSITY- INITIAL- 100. SUBSEQUENT- 90.

	ENTIRE STAND BEFORE AND AFTER THINNING							PERIODIC INTERMEDIATE CUTS				
STAND AGE (YEARS)	TREES NO.	BASAL AREA SQ.FT.	AVERAGE D.B.H. IN.	AVERAGE HEIGHT FT.	TOTAL VOLUME CU.FT.	MERCHANT-ABLE VOLUME CU.FT.	SAWTIMBER VOLUME BD.FT.	TREES NO.	BASAL AREA SQ.FT.	TOTAL VOLUME CU.FT.	MERCHANT-ABLE VOLUME CU.FT.	SAWTIMBER VOLUME BD.FT.
30	950	119	4.8	25	1530	360	0					
30	373	68	5.8	27	810	360	0	577	51	720	0	0
40	370	96	6.9	36	1330	920	0					
50	365	121	7.8	44	1970	1560	900					
50	211	85	8.6	45	1380	1170	900	154	36	590	390	0
60	210	106	9.6	52	1910	1690	2900					
70	209	126	10.5	58	2670	2420	6300					
70	129	90	11.3	59	1940	1780	5900	80	36	730	640	400
80	129	106	12.3	65	2560	2370	8600					
90	129	123	13.2	70	3200	2990	11400					
90	84	90	14.0	70	2370	2230	8800	45	33	830	760	2600
100	84	103	15.0	75	2900	2740	11400					
110	84	116	15.9	78	3430	3260	14100					
110	27	46	17.6	80	1390	1330	6200	57	70	2040	1930	7900
120	27	54	19.1	83	1700	1640	8100					
130	27	62	20.5	86	2030	1970	10200					
						TOTAL YIELDS				6940	5690	20700

MINIMUM CUTS FOR INCLUSION IN TOTAL YIELDS-- 320. CUBIC FEET AND 1500. BOARD FEET

DWARF MISTLETOE INFECTION DID NOT OCCUR DURING THE ROTATION OF 130. YEARS.

MERCH. CU. FT. - TREES 6.0 INCHES D.B.H. AND LARGER TO 4.0-INCH TOP.

BD. FT. - TREES 10.0 INCHES D.B.H. AND LARGER TO VARIABLE TOP LIMIT.

YIELDS PER ACRE OF EVEN-AGED STANDS OF PONDEROSA PINE
SITE INDEX 70
THINNING INTENSITY- INITIAL- 100. SUBSEQUENT- 100.

	ENTIRE STAND BEFORE AND AFTER THINNING							PERIODIC INTERMEDIATE CUTS				
STAND AGE (YEARS)	TREES NO.	BASAL AREA SQ.FT.	AVERAGE D.B.H. IN.	AVERAGE HEIGHT FT.	TOTAL VOLUME CU.FT.	MERCHANT-ABLE VOLUME CU.FT.	SAWTIMBER VOLUME BD.FT.	TREES NO.	BASAL AREA SQ.FT.	TOTAL VOLUME CU.FT.	MERCHANT-ABLE VOLUME CU.FT.	SAWTIMBER VOLUME BD.FT.
30	950	119	4.8	25	1530	360	0					
30	373	68	5.8	27	810	360	0	577	51	720	0	0
40	370	96	6.9	36	1330	920	0					
50	365	121	7.8	44	1970	1560	1000					
50	239	94	8.5	45	1530	1290	1000	126	27	440	270	0
60	237	114	9.4	51	2060	1820	2900					
70	235	133	10.2	58	2820	2540	6000					
70	154	100	10.9	59	2140	1950	5700	81	33	680	590	300
80	154	117	11.8	65	2800	2570	9100					
90	154	133	12.6	69	3460	3210	11900					
90	104	100	13.3	70	2630	2460	9400	50	33	830	750	500
100	104	114	14.2	74	3200	3010	12000					
110	104	129	15.1	78	3810	3600	15000					
110	32	49	16.8	80	1490	1420	6400	72	80	2320	2180	4300
120	32	58	18.3	83	1840	1770	8500					
130	32	68	19.7	86	2210	2140	10800					
						TOTAL YIELDS				7230	5660	21900

MINIMUM CUTS FOR INCLUSION IN TOTAL YIELDS-- 320. CUBIC FEET AND 1500. BOARD FEET

DWARF MISTLETOE INFECTION DID NOT OCCUR DURING THE ROTATION OF 130. YEARS.

MERCH. CU. FT. - TREES 6.0 INCHES D.B.H. AND LARGER TO 4.0-INCH TOP.

BD. FT. - TREES 10.0 INCHES D.B.H. AND LARGER TO VARIABLE TOP LIMIT.

YIELDS PER ACRE OF EVEN-AGED STANDS OF PONDEROSA PINE
SITE INDEX 70
THINNING INTENSITY- INITIAL- 100. SUBSEQUENT- 80.

	ENTIRE STAND BEFORE AND AFTER THINNING							PERIODIC INTERMEDIATE CUTS				
STAND AGE (YEARS)	TREES NO.	BASAL AREA SQ.FT.	AVERAGE D.B.H. IN.	AVERAGE HEIGHT FT.	TOTAL VOLUME CU.FT.	MERCHANT-ABLE VOLUME CU.FT.	SAWTIMBER VOLUME BD.FT.	TREES NO.	BASAL AREA SQ.FT.	TOTAL VOLUME CU.FT.	MERCHANT-ABLE VOLUME CU.FT.	SAWTIMBER VOLUME BD.FT.
30	950	119	4.8	25	1510	0	0					
30	374	28	3.7	23	410	0	0	576	91	1100	0	0
40	372	59	5.4	32	820	290	0					
50	332	79	6.6	40	1230	800	0					
50	253	64	6.8	41	1000	670	0	79	15	230	130	0
60	227	79	8.0	47	1350	1090	300					
70	191	86	9.1	54	1630	1420	1700					
70	191	86	9.1	54	1630	1420	1700	0	0	0	0	
80	156	87	10.1	60	1860	1670	3500					
90	124	83	11.1	64	1960	1790	5500					
90	124	83	11.1	64	1960	1790	5500	0	0	0	0	0
100	95	76	12.1	68	1920	1770	6400					
110	71	66	13.1	72	1780	1660	6300					
110	37	40	14.0	73	1080	1010	4000	34	26	700	650	2300
120	29	38	15.5	76	1090	1030	4400					
130	21	33	16.9	79	970	1010	4200					
						TOTAL YIELDS				3600	1660	6300

MINIMUM CUTS FOR INCLUSION IN TOTAL YIELDS-- 320. CUBIC FEET AND 1500. BOARD FEET

DWARF MISTLETOE INFECTION STARTED AT AGE 10. AND RATING WAS 6.0 AT AGE 130.

NOTE THAT NOT ALL SCHEDULED THINNINGS WERE POSSIBLE.

MERCH. CU. FT. - TREES 6.0 INCHES D.B.H. AND LARGER TO 4.0-INCH TOP.

BD. FT. - TREES 10.0 INCHES D.B.H. AND LARGER TO VARIABLE TOP LIMIT.

YIELDS PER ACRE OF EVEN-AGED STANDS OF PONDEROSA PINE
SITE INDEX 70
THINNING INTENSITY- INITIAL- 100. SUBSEQUENT- 90.

	ENTIRE STAND BEFORE AND AFTER THINNING							PERIODIC INTERMEDIATE CUTS				
STAND AGE (YEARS)	TREES NO.	BASAL AREA SQ.FT.	AVERAGE D.B.H. IN.	AVERAGE HEIGHT FT.	TOTAL VOLUME CU.FT.	MERCHANT-ABLE VOLUME CU.FT.	SAWTIMBER VOLUME BD.FT.	TREES NO.	BASAL AREA SQ.FT.	TOTAL VOLUME CU.FT.	MERCHANT-ABLE VOLUME CU.FT.	SAWTIMBER VOLUME BD.FT.
30	950	119	4.8	25	1510	0	0					
30	374	28	3.7	23	410	0	0	576	91	1100	0	0
40	372	59	5.4	32	820	290	0					
50	332	79	6.6	40	1230	800	0					
50	289	71	6.7	41	1100	730	0	43	8	130	70	0
60	256	85	7.8	47	1450	1150	0					
70	215	91	8.8	54	1720	1480	1500					
70	215	91	8.8	54	1720	1480	1500	0	0	0	0	0
80	175	92	9.8	59	1950	1740	3200					
90	138	88	10.8	64	2060	1870	5200					
90	138	88	10.8	64	2060	1870	5200	0	0	0	0	0
100	106	81	11.8	68	2030	1870	6600					
110	79	71	12.8	72	1880	1750	6500					
110	44	45	13.7	73	1220	1140	4500	35	26	660	610	2000
120	34	42	15.1	76	1200	1140	4700					
130	25	37	16.4	78	1090	1140	4600					
						TOTAL YIELDS				2980	1750	6600

MINIMUM CUTS FOR INCLUSION IN TOTAL YIELDS-- 320. CUBIC FEET AND 1500. BOARD FEET

DWARF MISTLETOE INFECTION STARTED AT AGE 10. AND RATING WAS 6.0 AT AGE 130.

NOTE THAT NOT ALL SCHEDULED THINNINGS WERE POSSIBLE.

MERCH. CU. FT. - TREES 6.0 INCHES D.B.H. AND LARGER TO 4.0-INCH TOP.

BD. FT. - TREES 10.0 INCHES D.B.H. AND LARGER TO VARIABLE TOP LIMIT.

YIELDS PER ACRE OF EVEN-AGED STANDS OF PONDEROSA PINE
SITE INDEX 70
THINNING INTENSITY- INITIAL- 100. SUBSEQUENT- 100.

	ENTIRE STAND BEFORE AND AFTER THINNING							PERIODIC INTERMEDIATE CUTS				
STAND AGE (YEARS)	TREES NO.	BASAL AREA SQ.FT.	AVERAGE D.B.H. IN.	AVERAGE HEIGHT FT.	TOTAL VOLUME CU.FT.	MERCHANT-ABLE VOLUME CU.FT.	SAWTIMBER VOLUME BD.FT.	TREES NO.	BASAL AREA SQ.FT.	TOTAL VOLUME CU.FT.	MERCHANT-ABLE VOLUME CU.FT.	SAWTIMBER VOLUME BD.FT.
30	950	119	4.8	25	1510	0	0					
30	374	28	3.7	23	410	0	0	576	91	1100	0	0
40	372	59	5.4	32	820	290	0					
50	332	79	6.6	40	1230	800	0					
50	327	78	6.6	40	1210	790	0	5	1	20	10	0
60	284	92	7.7	47	1570	1230	0					
70	238	98	8.7	53	1860	1590	1500					
70	238	98	8.7	53	1860	1590	1500	0	0	0	0	0
80	194	98	9.6	59	2060	1830	3100					
90	153	92	10.5	64	2140	1940	4900					
90	153	92	10.5	64	2140	1940	4900	0	0	0	0	0
100	117	83	11.4	68	2080	1900	6500					
110	87	73	12.4	71	1940	1790	6600					
110	53	50	13.2	72	1360	1270	4800	34	23	580	520	1800
120	41	47	14.5	75	1330	1250	5100					
130	30	41	15.8	78	1200	1270	4900					
						TOTAL YIELDS				2900	1790	6700

MINIMUM CUTS FOR INCLUSION IN TOTAL YIELDS-- 320. CUBIC FEET AND 1500. BOARD FEET

DWARF MISTLETOE INFECTION STARTED AT AGE 10. AND RATING WAS 6.0 AT AGE 130.

NOTE THAT NOT ALL SCHEDULED THINNINGS WERE POSSIBLE.

MERCH. CU. FT. - TREES 6.0 INCHES D.B.H. AND LARGER TO 4.0-INCH TOP.

BD. FT. - TREES 10.0 INCHES D.B.H. AND LARGER TO VARIABLE TOP LIMIT.

YIELDS PER ACRE OF EVEN-AGED STANDS OF PONDEROSA PINE
SITE INDEX 70
THINNING INTENSITY- INITIAL- 100. SUBSEQUENT- 80.

	ENTIRE STAND BEFORE AND AFTER THINNING							PERIODIC INTERMEDIATE CUTS				
STAND AGE (YEARS)	TREES NO.	BASAL AREA SQ.FT.	AVERAGE D.B.H. IN.	AVERAGE HEIGHT FT.	TOTAL VOLUME CU.FT.	MERCHANT-ABLE VOLUME CU.FT.	SAWTIMBER VOLUME BD.FT.	TREES NO.	BASAL AREA SQ.FT.	TOTAL VOLUME CU.FT.	MERCHANT-ABLE VOLUME CU.FT.	SAWTIMBER VOLUME BD.FT.
50	575	121	6.2	40	1920	1060	0					
50	575	121	6.2	40	1920	1060	0	0	0	0	0	0
60	447	116	6.9	46	2020	1400	0					
70	337	106	7.6	53	2040	1580	0					
70	337	106	7.6	53	2040	1580	0	0	0	0	0	0
80	246	95	8.4	59	1960	1640	1100					
90	174	80	9.2	63	1810	1580	2000					
90	174	80	9.2	63	1810	1580	2000	0	0	0	0	0
100	121	67	10.1	67	1640	1470	3000					
110	85	57	11.1	71	1480	1350	4100					
110	52	40	11.9	71	1060	980	3500	33	17	420	370	600
120	40	39	13.3	75	1070	1000	3800					
130	29	34	14.7	77	990	980	3800					
					TOTAL YIELDS					1410	1350	3400

MINIMUM CUTS FOR INCLUSION IN TOTAL YIELDS-- 320. CUBIC FEET AND 1500. BOARD FEET

DWARF MISTLETOE INFECTION STARTED AT AGE 10. AND RATING WAS 6.0 AT AGE 130.

NOTE THAT NOT ALL SCHEDULED THINNINGS WERE POSSIBLE.

MERCH. CU. FT. - TREES 6.0 INCHES D.B.H. AND LARGER TO 4.0-INCH TOP.

BD. FT. - TREES 10.0 INCHES D.B.H. AND LARGER TO VARIABLE TOP LIMIT.

YIELDS PER ACRE OF EVEN-AGED STANDS OF PONDEROSA PINE
SITE INDEX 70
THINNING INTENSITY- INITIAL- 100. SUBSEQUENT- 90.

	ENTIRE STAND BEFORE AND AFTER THINNING							PERIODIC INTERMEDIATE CUTS				
STAND AGE (YEARS)	TREES NO.	BASAL AREA SQ.FT.	AVERAGE D.B.H. IN.	AVERAGE HEIGHT FT.	TOTAL VOLUME CU.FT.	MERCHANT-ABLE VOLUME CU.FT.	SAWTIMBER VOLUME BD.FT.	TREES NO.	BASAL AREA SQ.FT.	TOTAL VOLUME CU.FT.	MERCHANT-ABLE VOLUME CU.FT.	SAWTIMBER VOLUME BD.FT.
50	575	121	6.2	40	1920	1060	0					
50	575	121	6.2	40	1920	1060	0	0	0	0	0	0
60	447	116	6.9	46	2020	1400	0					
70	337	106	7.6	53	2040	1580	0					
70	337	106	7.6	53	2040	1580	0	0	0	0	0	0
80	246	95	8.4	59	1960	1640	1100					
90	174	80	9.2	63	1810	1580	2000					
90	174	80	9.2	63	1810	1580	2000	0	0	0	0	0
100	121	67	10.1	67	1640	1470	3000					
110	85	57	11.1	71	1480	1350	4100					
110	60	45	11.7	71	1180	1080	3800	25	12	300	270	300
120	45	41	13.0	74	1150	1070	4000					
130	32	36	14.3	77	1030	1080	3900					
					TOTAL YIELDS					1330	1080	3900

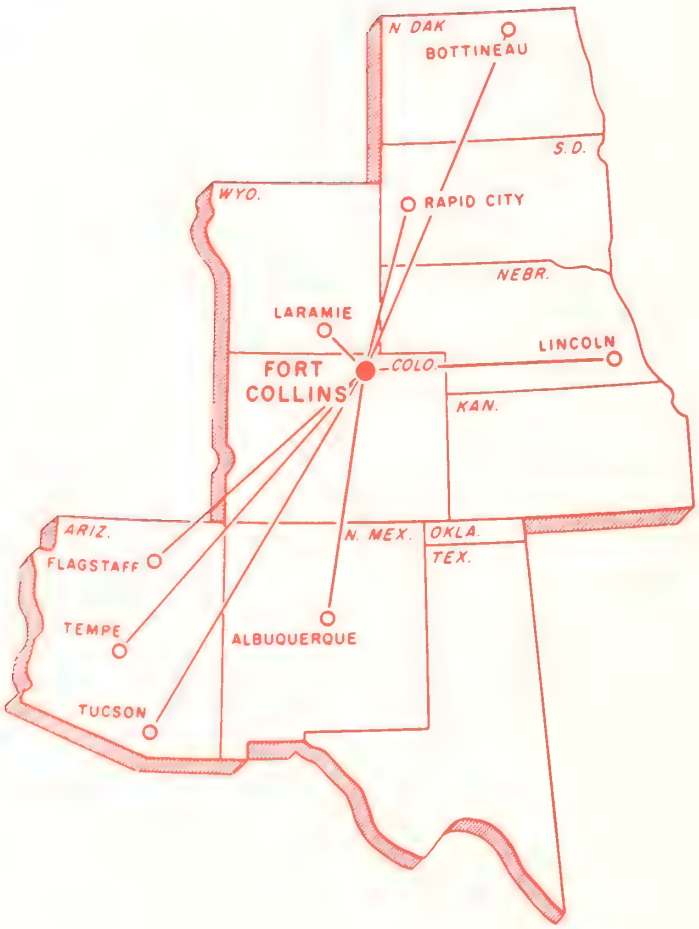
MINIMUM CUTS FOR INCLUSION IN TOTAL YIELDS-- 320. CUBIC FEET AND 1500. BOARD FEET

DWARF MISTLETOE INFECTION STARTED AT AGE 10. AND RATING WAS 6.0 AT AGE 130.

NOTE THAT NOT ALL SCHEDULED THINNINGS WERE POSSIBLE.

MERCH. CU. FT. - TREES 6.0 INCHES D.B.H. AND LARGER TO 4.0-INCH TOP.

BD. FT. - TREES 10.0 INCHES D.B.H. AND LARGER TO VARIABLE TOP LIMIT.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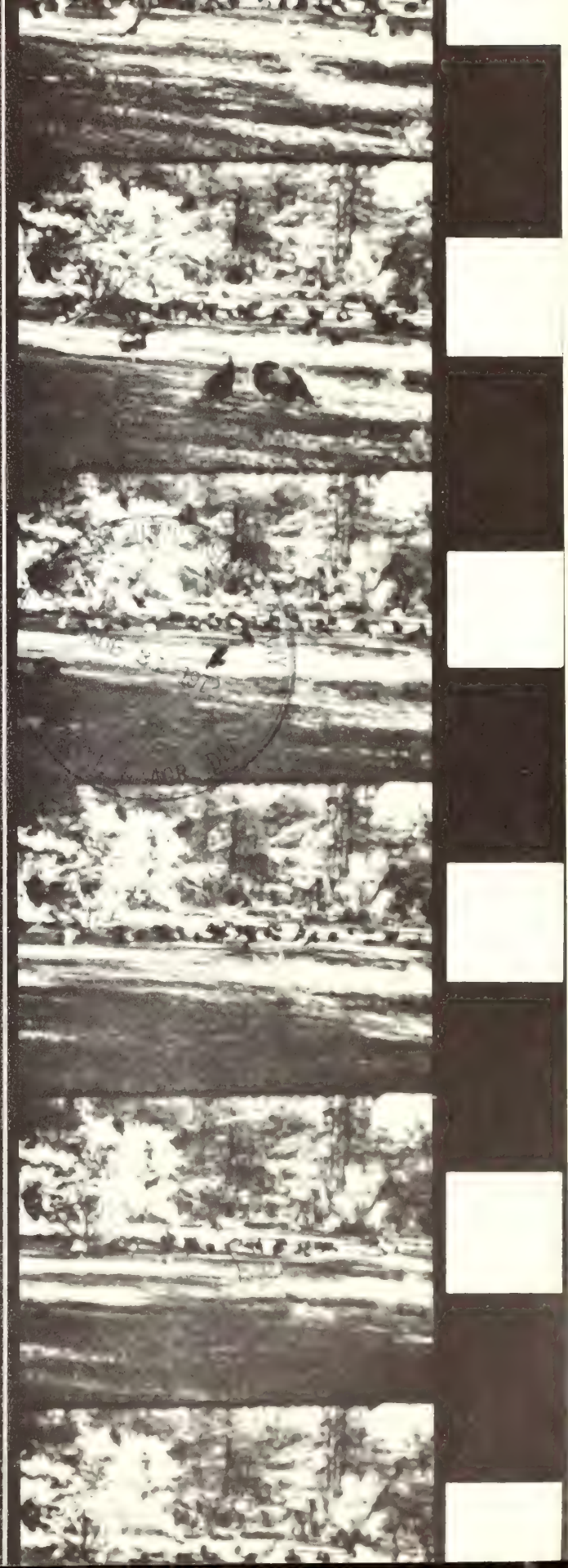

CONSTRUCTION OF AN 8-MM TIME-LAPSE CAMERA FOR BIOLOGICAL RESEARCH

by David R. Patton, Virgil E. Scott, and Erwin L. Boeker

USDA Forest Service
Research Paper RM-88
April 1972
Rocky Mountain Forest and Range Experiment Station
Forest Service
U. S. Department of Agriculture
Fort Collins, Colorado

Abstract

A time-lapse camera for use in biological research can be constructed from a super 8-mm movie camera. A single-frame release is activated through a solenoid controlled by an electronic timer. The unit is activated by a photo cell for daylight operation. Timing interval can be varied from 1/2 second to 60 minutes. With a 5-minute interval and 12 hours of daylight, one roll of film will last 25 days. The unit operates from a 6-volt d.c. power supply. Cost of camera, solenoid, and electronic timer is approximately $165.

Keywords: Wildlife techniques, biological research, time-lapse photography.

Acknowledgments

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SDA Forest Service
esearch Paper RM-88

April 1972

Construction of an 8-mm Time-Lapse Camera for Biological Research

by

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Construction of an 8-mm Time-Lapse Camera for Biological Research

David R. Patton, Virgil E. Scott, and Erwin L. Boeker

Introduction

Time-lapse photography is a valuable technique to replace observers in certain types of wildlife research. It compresses the time of a scene into a shorter viewing period; it is an instantaneous and systematic sample of an event. A review of technical data on commercial devices that met our specifications revealed most were too expensive (from $400-$1,200), and were not adapted to field use. It became apparent that if we wanted to use time-lapse photography in wildlife research, we would first have to develop the equipment. This paper presents one method for constructing a 8-mm time-lapse camera.

The time-lapse unit consists of a Vivitar [3] Super 8-mm movie camera with an electric motor, behind-the-lens light meter, automatic "f" stop, and 50-foot film cartridge. The single-frame release is activated by a solenoid attached to the side of the camera and controlled by an electronic timer.

During daylight hours the unit is turned off by a photo cell. The camera, timer, and solenoid are encased in a weatherproof aluminum box (fig. 1). Power is provided by a 6-volt battery. Any camera with a single-frame release or an electromagnetic shutter can be used with the timer and solenoid. Choice of camera will depend on the cost and operational features needed by the researcher.

[3] *Trade names and company names are used for the benefit of the reader and do not imply endorsement or preferential treatment by the U. S. Department of Agriculture.*

Construction Details

Weatherproof Case

The camera case is constructed from a deep drawn aluminum box (fig. 2). Holes are cut in the ends for a glass or plastic lens. Suitable lenses can be obtained from surplus meters or flashlights. Lenses are held in place with epoxy cement or a lens mount with screws. A hole for the solar unit is cut below the front lens. Two screws hold a cover over the side of the case.

A sheet of 1/16- x 8- x 9-inch aluminum is attached to the outside of the case by screws or rivets. Holes (1/4 inch) spaced at 1-inch intervals are drilled at the top and bottom. These holes are helpful when positioning the camera on a post or tree. Inside the case, a piece of plywood (1/2 x 1-1/2 x 3-1/2 inches) is glued to the side. The camera is held against the plywood by a No. 12-20 x 1/4-inch screw going through the top of the case into a light socket on top of the camera.

Figure 1.—Time-lapse camera in an aluminum case.

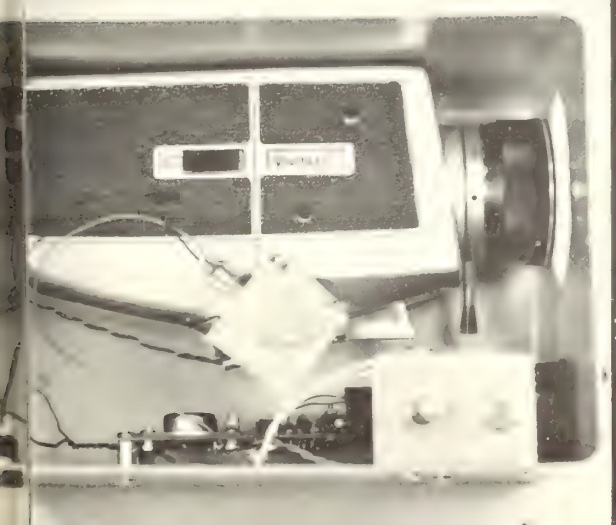


Figure 2.—Camera case constructed from aluminum box.

Holes for banana plug receptacles are drilled near the back of the case. Locations of the timer and control panel are not critical. Screw holes for locating these parts can be drilled after the camera has been positioned inside.

The aluminum box with a tight-fitting side cover makes a good weatherproof container. An alternative is to use plywood and coat it with epoxy resin. A piece of 1/2- x 20- x 20-inch plywood contains enough material to construct the case. Table 1 lists parts for the camera and case.

Electronic Timer

The electronic timer is constructed on a fiberglass board or printed circuit. Holes are drilled in the board so wire leads from the components can be connected on the underside according to the schematic (fig. 3). Components (table 2) are identified and located on the board as shown in figure 4 (gray lines show the actual connections).

There are five sets of connections leading from the timer: the power source, solenoid, reset, voltage control, and photo cell. All wire connections should be stranded No. 22 wire. A button switch and variable resistor (R25) are mounted on a control panel and located near the front of the case (fig. 1). Wires from the button switch connect to the reset points. The variable resistor connects to the points labeled R25 on the layout.

Two wires, one red (positive) and one black (negative) lead from the timer to two banana plug receptacles at the rear of the case. Receptacles also should be red and black. Solenoid wires from the timer have female connections that fit the flat terminals of the solenoid. Camera and photocell connections are identified on the layout and schematic.

Care must be taken to insure the positive (red) wire from the camera is connected to the positive banana plug receptacle. It is helpful if the pairs of connections from the timer to the photo cell, reset button, and R 25 are color coded.

Table 1.—Parts list for camera and case

Description	No. Needed	Approximate Cost
Camera, Super 8-mm, Vivitar Model 83	1	100.00
Aluminum box (Zero No. Z96-144-80)	1	6.95
Al. cover (Zero No. Z96-144-COT-1/2)	1	2.95
Screws, No. 8-32 x 1/4	16	.48
Screw, No. 12-20 x 1/4	1	.04
Nuts, No. 8-32	6	.18
Aluminum sheet, 1/16" x 8" x 9"	1	.50
Aluminum sheet, 1/16" x 1" x 1-1/2"	1	—
Lens, glass or plastic 2-3/4" dia. (minimum)	1	.30
Lens, glass or plastic 1-1/2" dia. (minimum)	1	.15
Plywood, 1/2" x 1-1/2" x 3"	1	—
Cork, 1/8" x 1/2" dia.	1	—
Solenoid, Dormeyer B24-255-A1	1	4.25
Cable, 2 conductor (red & black), stranded No. 22	10 ft.	1.25
Welding rod, 1/16" x 3"	1	—
Receptacles, banana plug	4	1.00
Jacks, banana plug	4	1.00
Cartridge case, ammo, 50 mm (surplus)	1	1.50
Spray paint, epoxy (Sears)	1	1.50
Conductor, quick disconnect (push-on type, female)	2	.10
	TOTAL	$122.15

The timer is mounted inside the case near the front of the camera on four 1/2-inch spacers. As a precaution against moisture, the timer can be sealed in potting compound or sprayed with plastic.

Photo Cell

Day operation of the camera is controlled by a photoelectric cell mounted below the camera lens and connected to the timer by wire leads. The cell is inserted in a holder behind a clear lens with a frosted back. A bayonet base for the photo cell is made from a T-1, 3/4 midget lamp. Glass is broken from the lamp and resin cleaned from inside the base. The cell is soldered to the base at the same points as was the lamp filament. Leads of the cell soldered to the base must be long enough so the cell just touches the glass of the cover lens. Parts for the photoelectric unit are listed in table 2.

Camera Modification

The Vivitar camera is modified to fit inside the aluminum case by removing the pistol grip handle. Two screws hold the handle to the camera base. When these screws are removed, the handle can be pulled from the camera and the connecting wires exposed.

The three wires (red, black, and white) in the handle should be disconnected and soldered to 6-inch leads so they may be connected to the power source. Both the red and white wires are positive and can be connected to one red wire. The white wire provides power to the automatic "f" step. On new models this wire may not be present.

Solenoid Modification for Single-Frame Release

A Dormeyer No. B24-255A1 solenoid is modified for use as the activator of the single-frame release. The flat end of the plunger is cut off at the end of the slot (fig. 5). The sharp end of the plunger also is cut off about 1/8 inch so that it can be drilled for insertion of a plunger pin. The end of the solenoid also must be drilled with a hole large enough to allow passage of the pin. An easy way to drill the solenoid and plunger for a good fit is to drill them both at the same time in a vise.

The plunger, after the ends have been cut off, is inserted in the solenoid and clamped in a vise so the plunger does not move. A hole is then drilled through the nubbin at the end of the solenoid and 1/4 inch into the plunger. A 1-5/16-inch pin is cut from 1/16-inch brass welding rod or a nail, and is soldered in the hole in the plunger.

The single-frame release receptacle on the side of the camera is removed and soldered over the nubbin at the end of the solenoid. The hole in the receptacle will have to be enlarged to allow the plunger pin to pass. Since the receptacle is plated brass, the plate material must be filed or sanded off before soldering to the solenoid.

The plunger must move freely in the solenoid so the pin can contact the single-frame release inside the camera. If the pin rubs against the sides of the solenoid the hole can be drilled larger. With the plunger all the way in the solenoid, the pin should stick out about 3/8 inch. This is a little longer than necessary, to allow for some adjustment.

The plunger is held inside the solenoid by a "stop" made from aluminum (1/16 x 1 x 1-1/2 inches) bent to an "L" shape. A piece of cork is glued to the end of the plunger to reduce noise. Two holes are drilled on the side of the solenoid for No. 8-32 screws to hold the stop in place. Screw holes in the aluminum stop are made oblong to allow for adjustment of the plunger.

Solenoid Adjustment

The camera is activated by connecting the leads to a 6-volt power source. The solenoid is screwed into the single-frame release hole on the side of the camera. The plunger is slowly pushed until a single frame is released. This should happen when the plunger is almost at the end of its travel. If a frame is released before the plunger is more than 1/16 inch from the end of the solenoid, the pin is too long. Adjustment is made by filing the pin. For smooth operation the pin should be sanded round at the end.

The camera stop is positioned against the plunger when the pin is just touching the single-frame release. It is important the stop does not hold the plunger too far into the solenoid. The plunger is slowly pushed until a "buzz" or slight click is heard. A noise indicates electrical contact has been made and the camera is drawing current. When contact

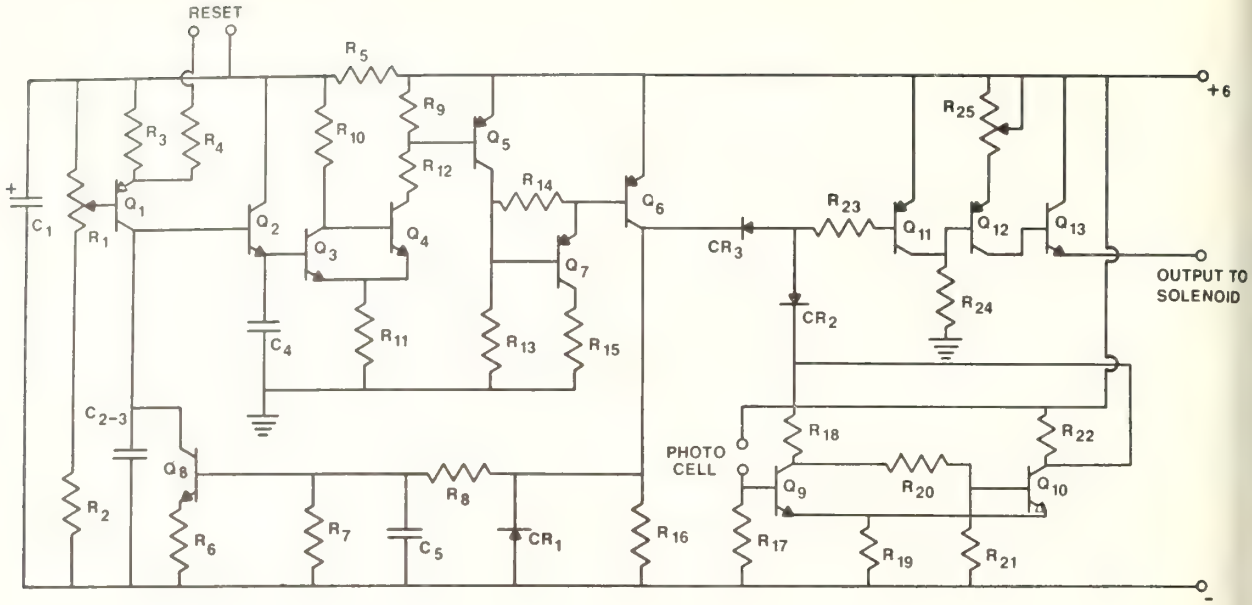
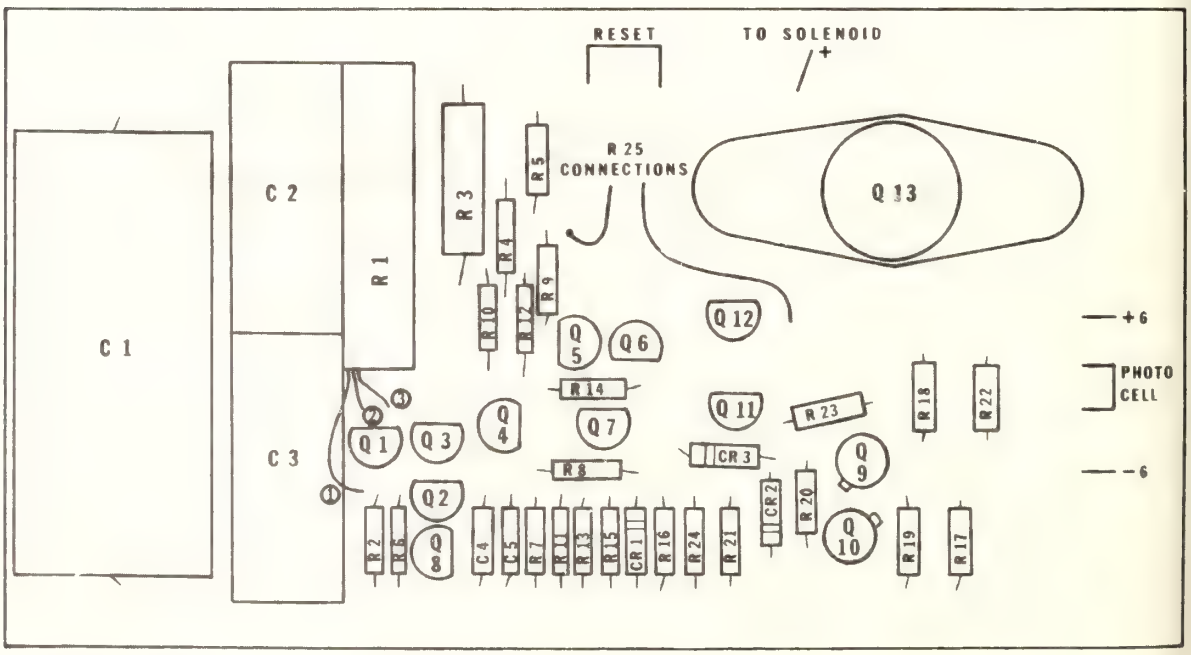


Figure 3.—Schematic for constructing electronic timer.



① YELLOW WIRE
② GREEN WIRE
③ RED WIRE

Figure 4.—Location of components and electrical connections.

Table 2.—Parts list for electronic timer

Description		No. Needed	Approximate Cost
RESISTORS			
R-1	10K variable (Bourns 271-1-103) .5 watt	1	$3.19
R-2,7	27K, 1/4 watt. 5%	2	.18
R-3	10 meg, 1 watt, 5%	1	.18
R-4,14,23	10K, 1/4 watt, 5%	3	.27
R-5	100 ohm, 1/4 watt, 5%	1	.09
R-6,13,17	3.3K, 1/4 watt, 5%	3	.27
R-8	100K, 1/4 watt, 5%	1	.09
R-9	220K, 1/4 watt, 5%	1	.09
R-10	820K, 1/4 watt, 5%	1	.09
R-11	56K, 1/4 watt, 5%	1	.09
R-12	39K, 1/4 watt, 5%	1	.09
R-15	680 ohm, 1/4 watt, 5%	1	.09
R-16	270 ohm, 1/4 watt, 5%	1	.09
R-18	9.1K, 1/4 watt, 5%	1	.09
R-19	240 ohm, 1/4 watt, 5%	1	.09
R-20	3.9K, 1/4 watt, 5%	1	.09
R-21	5.6K, 1/4 watt, 5%	1	.09
R-22	5.1K, 1/4 watt, 5%	1	.09
R-24	6.2K, 1/4 watt, 5%	1	.09
R-25	500 ohm, variable, wire wound, miniature 12.5 watt	1	4.80
CAPACITORS			
C-1	1000 mfd, 15 vdc, electrolytic (Sprague TVA 1163)	1	1.38
C-2,3	5 mfd, 50 vdc, mylar (EEC B42 A 505K)	1	5.20
C-4,5	.1 mfd, 25 vdc, monolithic, ceramic ± 10%, Erie red cap	2	1.80
DIODES			
CR-1	1N649	1	$3.25
CR-2,3	1N914	2	.69
TRANSISTORS			
Q-1,5,7,11	2N5087, Motorola	4	3.24
Q-2,3,4,8	2N5089, Motorola	4	3.92
Q-6,12	2N4403, Motorola	2	1.50
Q-9,10	2N2222, Motorola	2	2.10
Q-13	2N3055, Motorola	1	1.82
PHOTO UNIT			
Light, indicator with clear lens, non dimming Dialco No. 111-3830		1	2.15
Lamp, T 1-3/4, GE No. 328		1	.71
Photo cell, cds Clairex 907 HL		1	1.50
MISCELLANEOUS			
Spacers, brass 1/2" (No. 8-32)		4	.20
Wire, stranded No. 22		6 feet	.24
Switch, button (SPST)		1	.87
		TOTAL	$40.72

Certain uses of time-lapse photography will require a known time for individual frames. The easiest method is to place a clock in the lens field so its image will appear in the corner of a frame.

Hints for Good Results

The time-lapse camera should work properly if constructed without major change. Many combinations of solenoids, trip mechanisms, and timers were tested before arriving at a final design. The most difficult task in getting the camera to operate properly is in adjusting the solenoid. Before data are collected for research purposes, the unit should be allowed to operate continuously for several days.

Sometimes scratches or a slight "nick" in the solenoid plunger will cause a malfunction. It should be rubbed with a very fine emory cloth and then coated with graphite, teflon, or silicon lubricant. A malfunction can occur with the single-frame release inside the camera. In such cases the camera should be sent back to the factory for repair. It is wise to check a new camera completely so malfunctions can be corrected under warranty. Once the camera is modified, most companies will not honor the guarantee and will charge for repair.

When operating the camera in the field it should be placed on an immovable post or tree. The shutter speed is low (1/30 second), and any movement will cause an image blur when the single-frame release is used.

Moisture inside the camera could be a problem at certain times of the year. Fogging of the lens does occur and small bags of desiccant will help to prevent moisture from accumulating.

Amount of film exposed is shown by an indicator on the side of the camera. Footage must be read before removing film from the camera. When the film case is removed the indicator automatically returns to zero. To check the footage in the field, the camera has to be removed from its case. An alternative is to include a view window in the case during construction.

Since the solenoid must be removed each time the film is changed, it is best not to twist the solenoid too tight. The solenoid should be tightened only for a snug fit.

There are several additional features of this particular time-lapse unit that can be of use to the researcher. Time intervals from 1/2 second to 2-1/2 minutes are possible by making a direct connection across the reset button and adjusting the turns on R 1 to obtain the desired interval.

Another useful feature is exposure of more than one frame in short bursts. This is accomplished without the use of the solenoid. The positive wire from the camera is connected to the positive wire going to the solenoid from the emitter of Q 13. After this is done the camera trigger is pulled back and locked in the "on" position. The number of frames per "burst" is approximately 12.

Noise from activating the solenoid can be reduced by placing styrofoam inside the aluminum case. With some cutting the same styrofoam that came with the camera can be used effectively.

Component Suppliers

Most of the parts listed in tables 1 and 2 can be purchased from local stores or obtained from surplus equipment. Listed below are addresses of some companies that have components for the time-lapse unit.

Electronic components:

Allied Electronics
100 N. Western Av.
Chicago, Ill. 60680

Newark Electronics Corp.
500 N. Pulaski Rd
Chicago, Ill. 60624

Lafayette Radio Electronics
111 Jerico Turnpike
Syosett, L. I.
New York, N. Y. 11791

Aluminum boxes:

Zero Manufacturing Co.
1121 Chestnut St.
Burbank, Calif. 91503

Capacitors EEC B42A505K

Engineered Components Co.
2134 West Rosencrans Av.
Gardena, Calif. 90249

Total cost of parts, including camera, is approximately $165. Other cameras with a single frame release can be used and may be more desirable depending on individual needs. Prices of different makes of cameras will vary from $100 to $150.

Patton, David R., Virgil E. Scott, and Erwin L. Boeker.
1972. Construction of an 8-mm time-lapse camera for biological research. USDA Forest Serv. Res. Pap. RM-88, 8 p. Rocky Mt. Forest and Range Exp. Stn., Fort Collins, Colo. 80521.

A time-lapse camera for use in biological research can be constructed from a super 8-mm movie camera. A single-frame release is activated through a solenoid controlled by an electronic timer. The unit is activated by a photo cell for daylight operation. Timing interval can be varied from 1 2 second to 60 minutes. With a 5-minute interval and 12 hours of daylight, one roll of film will last 25 days. The unit operates from a 6-volt d.c. power supply. Cost of camera, solenoid, and electronic timer is approximately $165.

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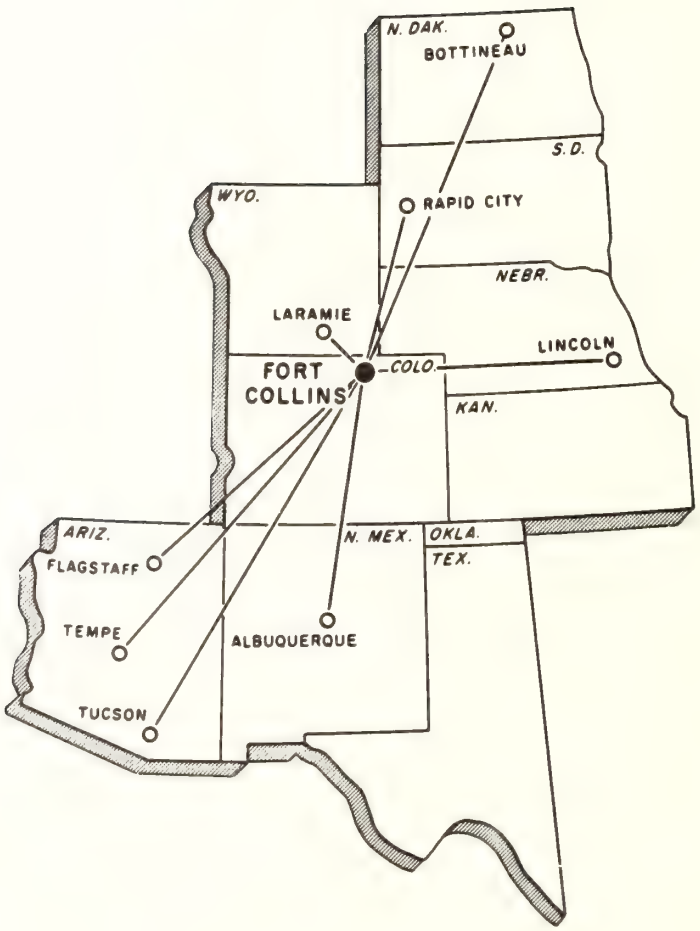
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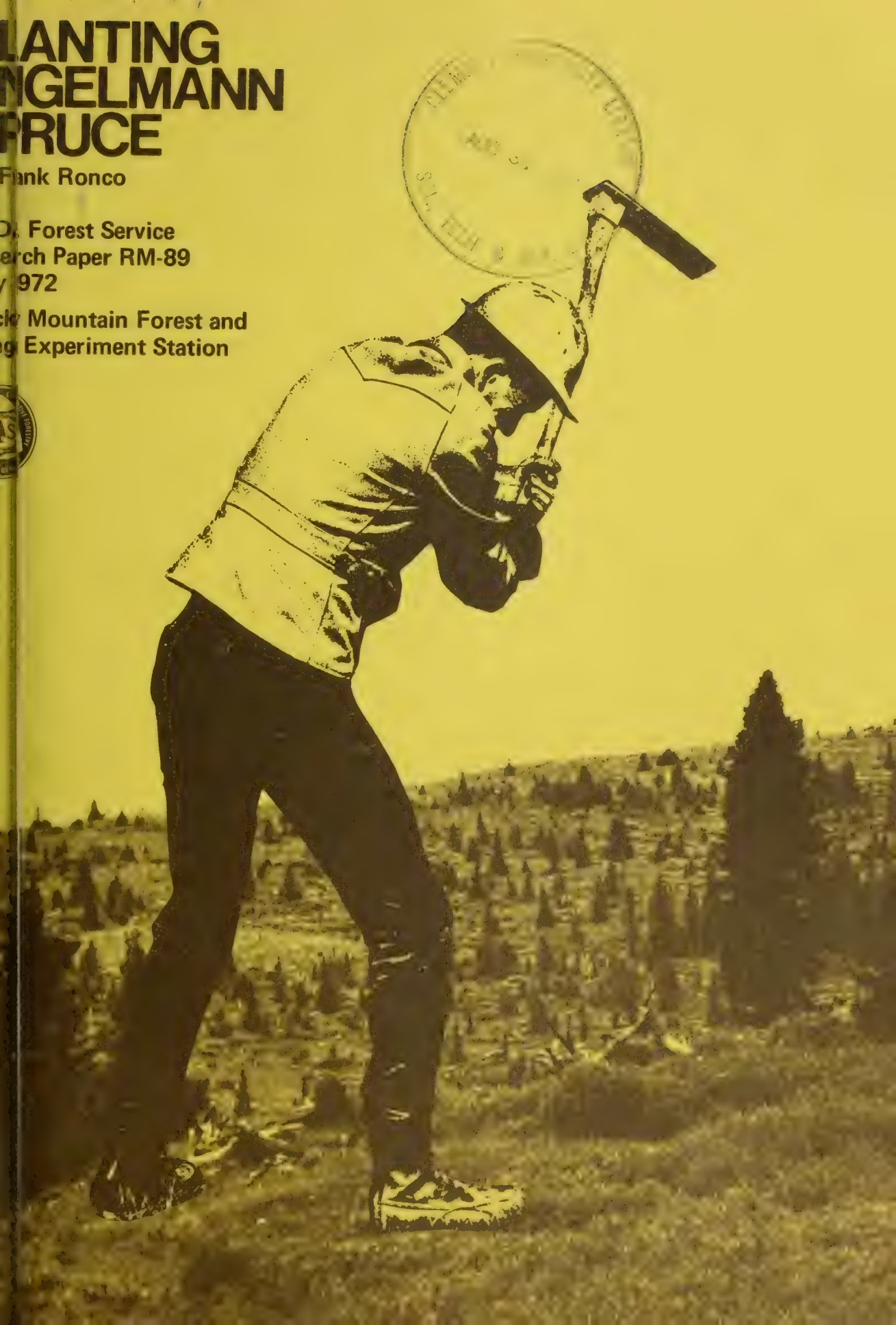

Abstract

Recommendations are provided to aid the forest manager in regenerating Engelmann spruce by planting in the central and southern Rocky Mountains. Reforestation operations covered include storage, transportation, microsite selection, site preparation, planting, plantation protection, and recordkeeping. The physiological and silvicultural requirements of spruces are discussed with respect to the harsh environment of the spruce-fir zone so that planting principles can be better understood.

Keywords: Picea engelmannii, planting, artificial regeneration.

ABOUT THE COVER:

High-elevation burn on the eastern approach of Vail Pass in central Colorado. The spruce-fir forest covering the area was destroyed by fire near the turn of the century, but natural regeneration is establishing slowly. Planting may be necessary to shorten the reforestation period on such areas, particularly where seed-producing trees are sparse or absent.

USDA Forest Service
Research Paper RM-89

May 1972

Planting Engelmann Spruce

by

Frank Ronco

Principal Silviculturist
Rocky Mountain Forest and Range Experiment Station[1]

[1]Central headquarters maintained at Fort Collins, in cooperation with Colorado State University.

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For convenient field use, the planting practices and recommendations in this Research Paper have been published separately in a smaller format (5½ by 8½ inches) as USDA Forest Service Research Paper RM-89A, "Planting Engelmann Spruce—A Field Guide." Copies of RM-89A are available from the Rocky Mountain Forest and Range Experiment Station, 240 West Prospect Street, Fort Collins, Colorado 80521.

Planting Engelmann Spruce

Frank Ronco

This guide was prepared to provide the il manager with the basic principles of plant- Engelmann spruce (Picea engelmannii ary) in the central and southern Rocky Moun- is. Research results are summarized, and physiological and silvicultural requirements spruces are discussed with respect to the h environment where they grow so that ting principles can be better understood. Reforestation is essentially a series of events starts with sowing in the nursery and ends hn planted seedlings become established. trim operations include cultivation, lifting, age, transportation, site preparation, plant- and protection of the plantation. Thus, a neration project is successful only to the tnt that each operation accomplishes a com- objective which, simply stated, is to keep ok in a vigorous condition. Survival can be ardized if any operation does not maintain necessary conditions required for healthy elings.

Although optimum conditions for each oper- n may not be fully known for spruces, ugh information is available to outline pro- dres that should increase the probability uccessful plantations. This guide sum- azes specific research on spruce, practices onstrated and proven successful in other gons (Limstrom 1963, Schubert et al. 1970, Vaeley 1954), and observation and experience.

Physiological and Silvicultural Requirements

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Examination of Engelmann spruce planta- on established on National Forests as early s e 1910's led Korstian and Baker (1925) o conclude that denuded areas in the spruce- r one could be successfully reforested if eedings were protected by "down logs, stumps, nd pen brush." Recent studies (Ronco 1970a) noted that such protection is necessary be- aus spruce seedlings are injured by high gh intensities—a phenomenon known as solar- atin—and generally survive poorly when ex- ose to full sunlight for prolonged periods. hlcotic (yellow-colored) foliage is the most om on visible evidence of light injury to seed- ng planted in the open.

Light injury has often been observed in many other shade-adapted or tolerant species, and appears to be related to the photosynthetic behavior of such plants. Shade plants, including spruces, have lower maximum photosynthetic rates and their photosynthetic mechanisms become light saturated at lower intensities than sun plants (intolerant species). Furthermore, they become increasingly susceptible to solarization the higher the light intensity increases above the saturation point. Open-grown spruce seedlings are particularly vulnerable since they are exposed to light intensities that are three to four times greater than those at saturation during most of the day.

The occurrence of solarization does not depend solely on the intensity of light. Duration of exposure is critical, and other factors, including high leaf temperatures and plant water stresses, may trigger the phenomenon. Thus, while light injury can be avoided simply by shading seedlings, the interrelationship of causal factors complicates prevention measures when all-day shade is now available. Shade during the hottest part of the day benefits planted spruce seedlings, even though they are exposed to full sunlight during morning and evening hours (Ronco 1961, 1970b). Midday and afternoon shade are necessary, probably because seedlings are subjected to higher temperatures and water stresses during these periods.

Water

The internal water balance of seedlings is probably of greater importance for growth and survival than any other plant-factor relationship. Water deficits alter the chemical composition of seedlings and decrease the rate of their physiological functions (Kramer and Kozlowski 1960). Deficits are created whenever water loss from transpiration exceeds water uptake by roots. Thus, water stresses may result from (1) lack of precipitation (drought); (2) high transpiration rates; or (3) reduced water uptake caused by cold soils, poor root conditions, or low moisture-holding capacity of soils.

Newly planted seedlings are most likely subjected to some water stress, but laboratory and field studies suggest that dehydration is

not the major cause of mortality observed in spruce plantations (Ronco 1970a). Water deficits in seedlings probably arise from the combined effects of transpiration and reduced water uptake rather than drought, since precipitation in the spruce-fir zone is generally adequate for seedling survival. For example, soil-moisture measurements in plantations on the White River Plateau in western Colorado during a particularly dry summer showed that moisture at root-zone depth was at or near field capacity throughout the summer and early fall. On the other hand, root initiation and elongation in newly planted seedlings is retarded due to low soil temperatures. Thus, normal transpiration losses coupled with slow root development may create water deficits in planted seedlings until roots become established.

More favorable water balances in seedlings can be obtained by using protective cover to reduce transpiration rates, which might otherwise be accelerated by exposing foliage to wind, or the heating effect of direct sunlight on needles. Little control can be exerted over those factors relating to water uptake, except to discard seedlings with spindly root systems. Similarly, precipitation is not controllable, but the amount of moisture available for seedling use can be increased by avoiding soil conditions that decrease water storage capacity (excessively rocky areas) or create a heavy drain on stored water (heavily sodded areas).

Temperature

Engelmann spruce is adapted to a cool environment, but new growth is still very sensitive to freezing temperatures, which commonly occur several nights during any growing season. All new growth on mature trees and seedlings—either natural or planted—is frequently killed when air temperatures are below freezing and heat loss from foliage is increased because of radiation to the clear nighttime sky (Ronco 1967). Both the severity and frequency of frost injury can be lessened, however, by reducing such radiant heat loss from seedling foliage and surrounding soil. Stumps, logs, slash, or a cover of live vegetation are effective barriers.

Daytime air temperatures, which rarely exceed 75° F. in the central Rocky Mountains, are probably not high enough to directly injure planted seedlings. However, elevated needle and soil-surface temperatures resulting from exposure to direct sunlight increases water losses from both seedlings and soil. Fortunately, the same type of cover that protects against freezing injury also tends to reduce water losses.

Planting Operations and Recommendations

Planting Stock

Korstian and Baker (1925) recommended 3-1 or 3-2 stock (top height about 4 to 6 inches and root length about 9 to 13 inches) with a good balance between top and root for planting in the Intermountain Region. They did not consider 3-0 stock suitable, even though of acceptable size, because it lacked fibrous root development. Schubert et al. (1970) suggested that spruce planting stock in the Southwest should have a stem caliper of 0.10 inch and well-developed tops and roots. No research has been conducted specifically to determine the size of spruce seedlings best suited for planting in the central and southern Rocky Mountains.

Observation of plantations on the White River National Forest, involving different age classes and sizes of stock over several years, suggested there may be some advantage to planting the larger seedlings from ungraded nursery stock. However, the studies also indicated that shading and good planting practices were more important than seedling size alone.

Spruce seedlings grown in the nursery, particularly from Colorado and Wyoming seed sources, have consistently varied widely in growth behavior; seedlings in individual beds may vary in height by several hundred percent. The smaller seedlings, while apparently healthy, appear to have slow, genetically controlled growth rates, which probably affect their ability to become quickly established when outplanted.

Grading should include provisions to cull the obviously small seedlings, as well as those that are too large to handle and plant practically. The guidelines below are based on limited experience in the Rocky Mountain Region, U. S. Forest Service; local conditions and experience may allow modification.

Recommendations:

1. Tops should not be shorter than 3 to 4 inches; they should be well developed with not less than two to three branches.
2. Roots should not be shorter than 5 to 6 inches; they should be compact, fibrous, and well developed with several lateral roots.
3. Tops and roots should be well balanced (low shoot/root ratio).

Planting Season

The time of year when seedlings are planted influences the success of plantations, particularly under short growing seasons and difficult environmental conditions. The probability of a successful spruce plantation is greatest when seedlings are planted in the spring. Soil moisture following snowmelt is maximum and weather conditions are favorable. Furthermore, seedlings have the benefit of an entire growing season to develop and overcome the shock of planting. To be most advantageous, however, seedlings should be planted in spring immediately after snowmelt; delay should be only long enough for free water to drain from the soil so that it can be properly packed around seedling roots. In many instances, roads will have to be cleared of snowdrifts to make most efficient use of the short planting season, and to plant under optimum soil-moisture conditions.

Spring plantings should be organized to take advantage of the conditions afforded by aspect. Plant southwest- and south-facing slopes first; east and north slopes last. In addition to facilitating access to planting areas, such scheduling will tend to lengthen the planting season by extending the period over which soil-moisture conditions are more favorable.

Local experience and judgment will be needed to determine when planting should be terminated in the spring, or temporarily suspended because of unfavorable planting conditions. The planting season in the spruce-fir zone normally extends from about May 25 to June 25. In years of late snowmelt, however, the season may be extended somewhat, but no seedlings should be planted after July 10 or they will not have sufficient time to harden off. The length of the planting season depends primarily on available soil moisture, but unseasonably high temperatures would also be sufficient reason for terminating planting because of the adverse effect on transpiration. Similarly, planting may be temporarily halted during the regular planting season because of unseasonably warm temperatures, especially if they are forecast for several consecutive days.

Summer and fall planting are **not** recommended in the spruce-fir zone for several reasons. **First,** good stock would not available. Seedlings lifted in the spring and stored for summer planting would be subjected to the adverse effects of prolonged storage, whereas nursery stock lifted in early fall before the seedlings are fully dormant would be in poor physiological condition. **Second,** by the time nursery seedlings can be safely lifted in late October or November, the high-elevation sites are generally inaccessible. **Third,** in those instances where good weather does permit fall planting, it also makes success less certain. Without a protective cover of snow, seedlings may be desiccated (winterkilled) because of an imbalance between transpiration and water uptake. Furthermore, cold soil at this time of year retards or even prevents root growth, and seedlings do not have the benefit of a well-developed root system to reduce the possibility of winterkill. Finally, seedlings will break dormancy if planted before temperatures and photoperiods prevent growth, but they are subjected to freezing fall temperatures nearly every night before shoots can fully develop—normally about 7 to 8 weeks. Subsequent frost injury to the new growth substantially increases mortality, and growth of surviving seedlings is lessened the following spring.

Recommendations:

1. Planting should be completed before June 25. Do not extend planting season beyond July 10.
2. Plant southwest- and south-facing slopes first; east and north slopes last.
3. Terminate spring planting when soil moisture becomes depleted, or temperatures are unseasonably high.
4. Temporarily suspend planting during the regular season if temperatures are unseasonably warm, particularly on clear days with dry winds.

Storage Principles

Nearly all planting operations in the Rocky Mountains require seedlings to be lifted from the nursery while they are still dormant, and stored until planting areas are free of snow. Dormancy must not only be maintained during storage, but transpiration and respiration also must be curtailed to prevent water stress and excessive loss of stored food reserves. These latter objectives are particularly important because first growth after planting depends mostly on stored food reserves, and water deficits alter the chemical composition and physiological functions of seedlings.

Seedlings should be treated as dormant plants, not only while stored at the nursery, but also during transit and periods of local storage. Optimum storage conditions—temperature between 34° and 36° F. and relative humidity over 90 percent—may not be readily attained outside the nursery, but for periods of 1 week or less, temperatures around 40° F. and humidities near 50 percent can be tolerated.

Molding is a major problem during extended storage of seedlings in nurseries (Hocking and Nyland 1971), but it is not likely to be a threat during short storage periods encountered in the field. Factors involved in molding include high relative humidities, free water on foliage, high storage temperatures, duration of storage, species susceptibility, and the presence of inoculum in soil adhering to foliage or packing materials.

Extended storage.—Adequate facilities are available at the nursery for storage extending over several weeks or a few months. Even though low temperatures depress physiological activities, respiratory losses of food reserves in spruce seedlings may still be high enough after long storage to reduce survival. [2]

Recommendations:

1. Spruce seedlings should not be stored over 3 months.
2. Extended storage should not be attempted locally since adequate facilities and trained personnel are not readily available.

Transit storage.—Methods of transporting stock will depend on ambient air temperatures and hauling distance. Long-distance transport under warm to hot temperatures will require controlled-temperature refrigeration units or insulated containers which can be held under 40° F. with ice. For short trips up to a few hours' duration, when air temperatures are cool to moderate, seedlings can be transported most conveniently in trucks with enclosed beds.

If open-bed trucks are used and seedlings are packaged in bundles, care must be exercised to prevent seedlings from drying. Cover the bundles with a tarpaulin that allows air to circulate over seedlings, but block high-speed, turbulent air flows created by moving vehicles. Use only canvas covers, since plastic materials transmit and trap solar heat. Covers should also be tied securely so that seedlings are not mechanically injured by flapping covers during high-speed travel.

Seedlings packed in sealed bags (polyethylene or polyethylene-lined paper) will not be dehydrated by air movement during transit in open-bed trucks, but cover will still be needed. Unless sealed bags are shaded from direct sunlight, temperatures inside may rea levels that are injurious or even lethal seedling tissue. Even if the higher temperatu are not directly harmful, they may foster grow of molds.

Temperatures around packaged seedlin transported in enclosed or tarpaulin-cover truck beds can usually be kept low enou by including block ice and wetting the co before leaving the nursery. Travel can restricted to nighttime hours if daytime temperatures are too high.

Recommendations:

1. Maintain temperature of seedlings between 34°-40 during transit.
2. Cover bundles or bags carefully with canvas paulins—Do not use plastic—when seedlings are tr ported in open vehicles.
3. Be particularly careful to keep sealed bags ou direct sunlight.

Local storage.—Storage problems are m severe in the field, because limited facilit on the planting site make temperature cont more difficult. Consequently, the maxim number of trees in storage should be limi to a 1-week supply. Well-insulated stor sheds that can be cooled by ice or snow sho be used in the absence of mechanical refrig tion (see appendix). If such facilities are available, cool, moist cellars or even sn banks would be suitable substitutes, but se lings should be held for shorter periods beca storage conditions will be less favorable.

Solidified carbon dioxide (Dry Ice) is recommended for cooling storage rooms cause gaseous carbon dioxide in high con trations disrupts the physiological processe respiration and water transport, and may e be toxic to seedlings in extremely high c centrations. Furthermore, humans may asphyxiated in tightly sealed storage roo particularly if work is performed near f level, since the heavier carbon dioxide se and displaces oxygen.

Seedlings must also be protected aga freezing while in storage or transit. Altho many conifers, including some species of spr have been satisfactorily stored at temperat below 32° F., such storage requires more cor than can be maintained under field conditi Seedlings that are frozen too rapidly or w they are not fully dormant may be serio damaged.

[2] Ronco, Frank. Food reserves of Engelmann spruce planting stock. (Manuscript in preparation at Rocky Mt. For. and Range Exp. Stn.)

Packing material around roots in bundled
es in storage may require rewetting occasion-
to prevent seedling desiccation. To deter-
ne the need for water, a small amount of
agnum moss can be pulled from the bundle
squeezed in the hand; if **any** water is
ssed out, the material is sufficiently moist.
t is necessary to prepare moss for planting
tainers or to repack seedlings from damaged
dles, the proper moisture content can be
ined by soaking moss overnight and then
ning for at least a half hour.

mmendations:

aintain temperature between 34° and 36° F.
nit storage to 7 days; where storage temperatures
proach or exceed 40° F., then no more than
days.
e ice, snow, or mechanical refrigeration to cool
rage rooms—**do not use Dry Ice.**
tect seedlings against freezing.
range bundles or bags on racks so that air can
culate around each package—seedlings may over-
at if packages are stacked.
e precautionary measures if mold should develop
der field storage conditions:
Lower temperature or shorten storage period.
Provide air circulation around foliage.
Keep foliage dry.
Rewet packing material in bundles with a per-
orated tube, attached to water hose, that will
each roots. Drain excess water.
Do not water seedlings in sealed bags. If bags
re damaged and drying is evident, repack seed-
ings in open-end bundles before rewatering.

torage in planting containers.—Field per-
el will be concerned with individual seed-
g for the first time as packaged seedlings
ransferred to bags or trays. Exposed
ings must be protected against desiccation
wind and sun, which would soon kill most
er roots and seriously decrease survival.
equently, seedlings should be transferred
sheltered work areas, such as storage sheds,
erected at the planting site, or clumps
ees when the size of the job does not
nt more elaborate facilities.
are must also be used in separating inter-
d roots of packaged seedlings before they
laced in individual containers. Damage
e lessened if the pulling force during
ation is parallel to the stems. For opti-
moisture conditions in planting containers, spread seedlings thinly, with roots in contact with alternate layers of moist sphagnum moss. Seedlings can then be easily removed for planting.

Storage in bags or trays is simply an extension of storage begun in the nursery, and is subject to the same moisture and temperature requirements. Packed containers can be kept for several days under the same conditions recommended for bundles, but time becomes critical after containers are issued to planters.

Container-held seedlings cannot be maintained at favorable temperatures for long periods on the planting sites. Planters should minimize the length of time seedlings are kept in containers and place containers in any available shade whenever possible. Water loss can be more easily controlled, but depends largely on proper supervision, experience of planters, and type of container. Experienced planters, who understand the importance of plant-water relations, can satisfactorily use bags without unnecessarily exposing roots of seedlings remaining in the bag as individual trees are removed. Some supervisors have found trays better suited for inexperienced crews because seedlings are extracted more easily. Furthermore, trays of seedlings can also be covered with burlap, thus reducing water loss from transpiration.

Seedlings in containers may become desiccated if packing material around roots becomes dry and is not remoistened with water or snow throughout the day. Free water in containers during this phase of the operation is probably not critical, since roots are not inundated for long periods. However, aeration would be better if planters were instructed to drain water as it accumulates.

Recommendations:

1. Do not expose roots to sun and wind when transferring seedlings from bundles or sealed bags to planting containers.
2. Prevent undue breakage of roots when handling seedlings.
3. Keep roots covered at all times with moist sphagnum moss.
4. Place container in shade whenever possible.
5. Suspend planting operations on clear days with dry winds and high temperatures.
6. Limit the time seedlings are kept in containers on the planting site as suggested for atmospheric conditions shown on the following page:

	Container time on—	
	calm day*	windy day*
	(Hours)	
High humidity:		
Cool (under 55° F.)	8	4
Warm (55°-70° F.)	4	2
Hot (over 70° F.)	2	1
Low humidity:		
Cool (under 55° F.)	2	1
Warm (55°-70° F.)	2	1
Hot (over 70° F.)	1	1

*On clear days, direct radiation will increase the heat load on containers, and shorter holding periods are advisable whenever practical.

Spot Selection

Suitable microsites for planted seedlings frequently have not been utilized because (1) spots were not easily accessible due to slash accumulations, (2) planters were unaware of the silvicultural requirements of spruces, or (3) demands for uniform spacing were unrealistic.

Most planters tend to plant open areas rather than suitable habitats close to stumps and logs because less work is involved. Branches and other debris often hinder access to spots, and once the spot is reached, footing may be insecure or space restrictions limit freedom to use planting tools effectively. Use of suitable spots can be increased by close supervision and training programs that emphasize the impact of solarization and potential water stress on spruce seedlings. Figures 1-8 illustrate effective use of cover in an operational plantation, as well as examples where training and supervision could be intensified.

Protective cover is usually scattered unevenly on spruce plantation sites. Attempts to space seedlings uniformly, even though desirable for full stocking, result in many trees being planted without protection. Planting in the open is usually wasted effort because of the high mortality rate of exposed seedlings. Spacing must be determined, therefore, by the availability of suitable planting spots rather than number of seedlings for optimum stocking. Consequently, seedlings will be spaced irregularly, and plantations will resemble natural stands more closely in that trees will be grouped in patches of variable size.

Recommendations:

1. Plant only those spots where seedlings are protected by stumps, logs, slash, or an open cover of live vegetation (see following section on Site Preparation). The preferred location is on the north side of cover; the east side may be used if preferred spots are unavailable, but avoid spots on the west side of logs where heating is more intense.
2. Knock loose bark from logs and stumps.
3. The seedling should be planted no more than 3 inches from protective cover unless the latter is high enough to cast a wide shadow that will envelop the seedling.
4. Spacing between seedlings should not be less than 4 feet when planting alongside long logs or in areas where protective cover is clustered.
5. Avoid planting in depressions where silt can smother trees.
6. Plant with roots in moist soil—generally, soil is too dry when a handful does not form a ball when squeezed.
7. Select spots that are relatively free of rocks to increase the volume of water-holding soil in the root zone.
8. Avoid planting on small mounds or hummocks, which tend to dry rapidly.
9. Avoid planting in areas with an extensive cover of dense sedge or grass sods (see following section on Site Preparation).
10. Emphasize that additional effort and time required to plant in properly located spots is compensated for by increased chances for survival.

A

Figure 1.—More effective protection with same effort. Seedling in (A) is partially protected by gs placed by planter. By simply reversing order in which logs were positioned (B), the seedling as shaded more fully by the log to the south (at left of center). Seedlings can be given maxi- um protection when logs are arranged in a "V" configuration, with the point toward the south, nce shade is provided from morning through afternoon.

B

A

Figure 2.—Branches or small-diameter logs provide little or no shade. Small logs, (C), might offer enough protection if they were arranged differently. Similarly, the preferred microhabitat

B

C

he north side of the log, (D), could have been improved by laying another log on the existing
so that the seedling would be shaded from the west (right of photograph), and by moving
ing log closer to the seedling.

D

A

Figure 3.—Conscientious attempt at protection fails. Planter spent considerable effort and time erecting tepee cover (A, reconstructed for illustration), but structure collapsed (B), leaving seedling exposed to full sunlight. Structures should have sufficient strength to withstand the weight of accumulated snow.

B

igure 4.—Error in spot selection. Seedling planted on the west side of a small log is fully
xposed to radiation most of the day, especially during the hot afternoon hours.

igure 5.—Shade from log fully utilized. Seedling is within 3 inches of the east side of log.
uch a spot would be optimum with little additional effort expended by laying a nearby log across
he existing one so that seedling is also shaded from the south.

Figure 6.—Cover still effective when seedling not close to log. Seedlings can be planted farther than 3 inches from large logs, (A), or those elevated above the ground (B).

Figure 7.—Vegetation may be effective cover. Caution should be used, however, when p viding live shade until more experience is gained concerning the effect of competition for moist

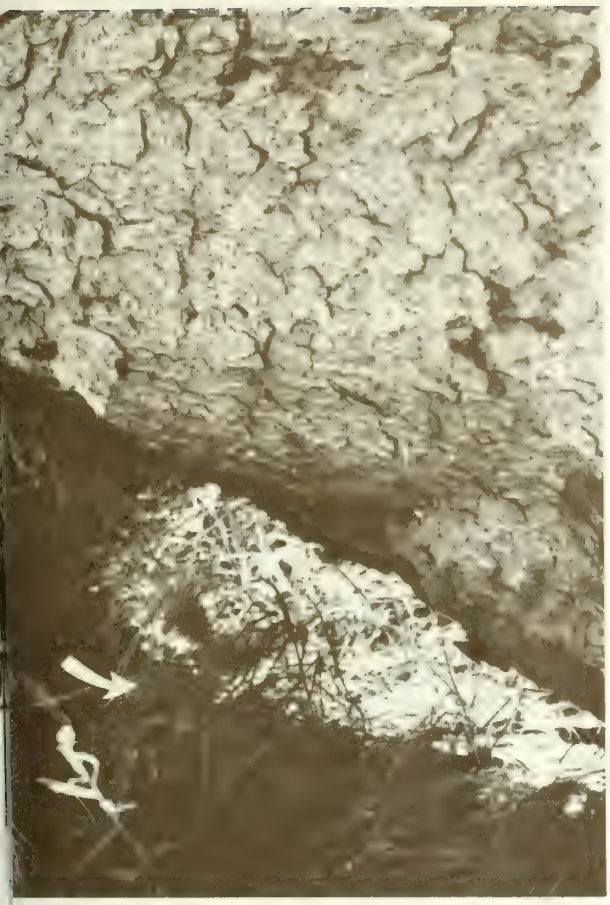


Figure 8.—Unnoticed hazards may jeopardize survival. The seedling has been properly planted with adequate protection, but it could be smothered if bark sloughs from log. With very little effort, bark can be knocked off with a mattock.

Site Preparation

The objective of site preparation is to manipulate some of the environmental factors affecting tree growth and survival—namely, soil moisture, light, and temperature of soil and air. The degree of control attempted will depend on local climate, soil properties, topography, vegetation density, and most importantly, the physiological and silvicultural requirements of the species planted. Obviously, without prior knowledge of seedling needs, attempts at site preparation could produce detrimental as well as beneficial effects. Site preparation is further complicated in that individual environmental factors cannot be manipulated without affecting others.

Site preparation measures for spruce plantations probably require more consideration than for most other species because of the complex relationship between the environment and seedling requirements. For example, warmer soils and increased moisture availability accompanying complete vegetation removal would benefit seedlings; but because of their sensitivity, seedlings would be more prone to severe injury from intense light and frost. Therefore, in the absence of logs or stumps, live vegetation may be desirable as protective cover even though it competes with seedlings.

Hand scalping will probably be adequate for most planting operations. Aboveground parts of plants are totally removed, but lateral roots from vegetation surrounding the scalp usually remain active. Thus the zone of soil released from the competitive effects of vegetation tapers rapidly below the ground surface, and the extent of the soil column freed of competition depends on the size of the scalped area.

Site preparation with heavy machinery should not be attempted in the spruce-fir zone without fully considering management goals and potential effects on the site. Removing vegetative competition or treating slash for fire or bark beetle control can adversely affect plantation establishment by destroying microsites that afford protection for planted seedlings. Conversely, machines could be used to obtain better distribution of favorable microsites over the plantation by rearranging logs. Exposure of mineral soil during such operations would also create favorable seedbeds, which might result in supplemental stocking from natural regeneration.

In areas where hand scalping is unsatisfactory, vegetation may be controlled by such machine methods as disking, furrowing, mounding, ridging (berms resulting from plowing), and bulldozing. Where competing vegetation consists of relatively tall brush species that form dense cover, complete removal or cleared strips of bulldozer-blade width may be desirable. These machine methods have proven successful for other species, but they have not been thoroughly tested for Engelmann spruce plantings. The use of machines in wet areas to form mounds or ridges, to elevate roots above the water table, is not recommended for spruce planting, because the probability of regenerating such sites is low.

The effectiveness and suitability of different species of plants as protective cover for spruce seedlings is not fully known. Korstian and Baker (1925) noted that moderately dense stands of aspen (Populus tremuloides Michx.) without a heavy understory of shrubs and herbaceous plants were favorable sites for planting spruce. Observation of natural and artificial regeneration in several areas of the central Rocky Mountains showed that fewer live seedlings were found in the open than where they were protected by brushy plants—willows (Salix spp.) and potentilla (Potentilla fruticosa)—and tall herbaceous species such as fireweed (Epilobium angustifolium). These species, and probably others of similar growth habits, apparently can provide shade without seriously depleting soil moisture. The circumstances also suggest that precipitation and moisture-holding properties in some parts of the spruce-fir zone are not major considerations in determining the degree of site preparation needed.

In contrast, mortality of natural and planted spruce seedlings has been recorded where seedlings were established near clumps or between scattered individual plants of sedges and grasses, which spread to form a solid, dense cover with roots completely occupying the soil. Some mortality was attributed to root competition, and part to smothering by cured vegetation compacting under the weight of snow. The probability of regenerating areas with an extensive cover of dense sod is low, even with considerable effort and expense, and planting is not recommended.

Because of the diversity of site conditions, as well as financial and manpower limitations that may be encountered, each plantation must be **considered individually** to determine the degree of site preparation needed for best survival. Consequently, the following recommendations are presented as suggestions or alternatives.

Recommendations:

1. Plant recent cuttings and burns before they are invaded by meadow vegetation.
2. Regardless of the need for scalping or the method of treatment, save all microsites created by stumps, logs, and other material.
3. Hand-scalped spots should not be smaller than 18 to 24 inches square.
4. Machine-scalping with disks or plows (furrowing or ridging) should leave vegetation-free areas 1.5 to 2 feet wide.
5. Mounds, either machine or hand constructed, should be 14 by 14 by 7 inches minimum size.
6. Use willows, potentilla, fireweed, or plants of similar growth habit for protection only when inert objects are not available.
7. Underplanting in aspen groves should be limited to stands with moderate crown density and light cover of understory vegetation.

Planting

The primary consideration in planting is to obtain intimate contact between mineral soil and roots. Ideally, the technique for planting expensive ornamentals—spread roots over a mound of soil, carefully compacting soil around roots, and filling bowl around plant with water—would be best for bare-rooted spruce seedlings. Obviously, such a practice would not be feasible in operational plantings.

In many areas of the United States where soils, topography, and environmental conditions are favorable, machines and planting bars have proven successful. In the spruce-fir zone, however, such flexibility is normally not possible. Machine planting would not only be impractical because of interference from rocks and roots in the soil, and objects on the surface needed for protection, but soil compaction around seedling roots also would not be sufficient. Slit planting can be used in light or medium soils, but in heavy soils found on some spruce sites, the combination of poor compaction and a harsh environment would reduce survival.

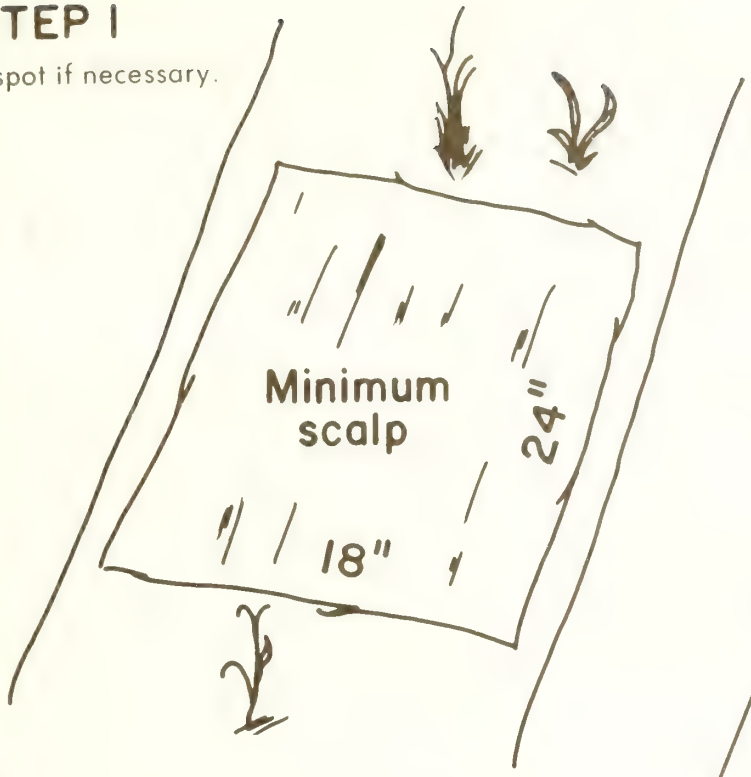
The hole method is preferred for planting spruce, since it resembles the technique used for ornamentals if properly done. Holes are generally dug with planting mattocks, but power-driven augers have proven satisfactory in lighter soils free of dense roots and rocks, and covered with little or no litter. Regardless of the type of digging tool used, techniques for setting seedlings in holes are similar. Power-auger operators, however, should be cautioned against digging holes so far in advance of planters that excavated soil dries before seedlings are set.

Recommendations:

1. Use the hole method; dig holes with mattock hand tools, or power augers where soil conditions permit.
2. Insist that planters do professional work as illustrated in the following steps:

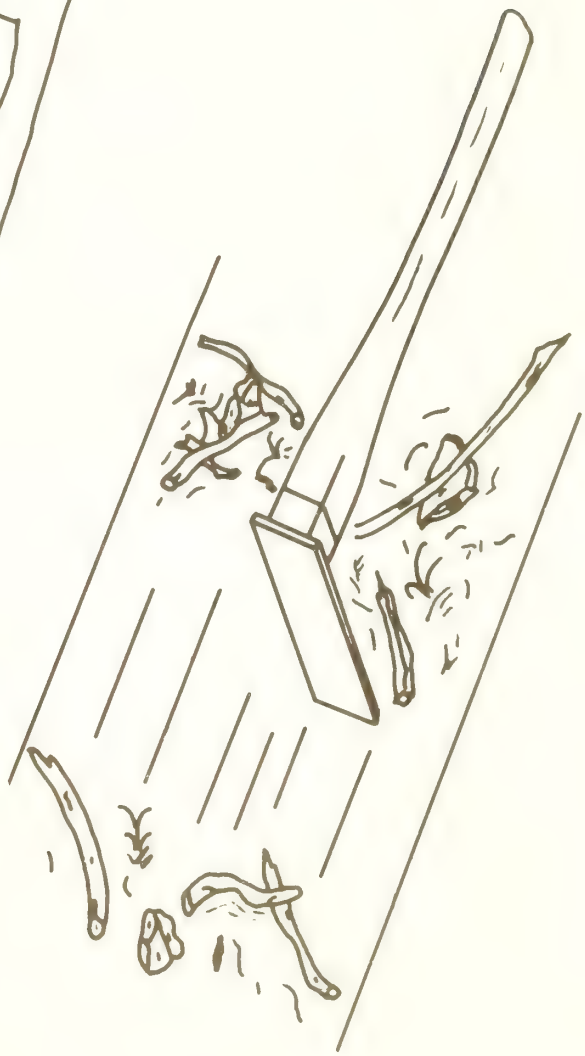
STEP 1

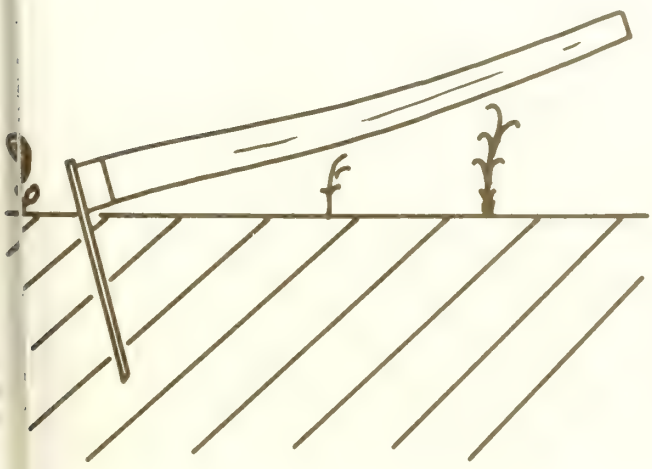
calp spot if necessary.



STEP 2

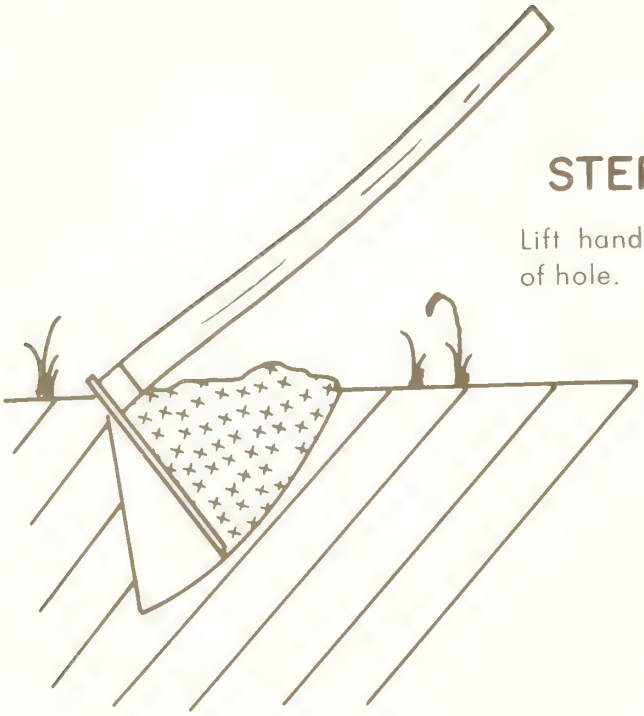
Remove live vegetation, litter, dry soil, or other debris from surface of spot with mattock to eliminate material that may fall into the hole and prevent intimate root-soil contact when hole is refilled.





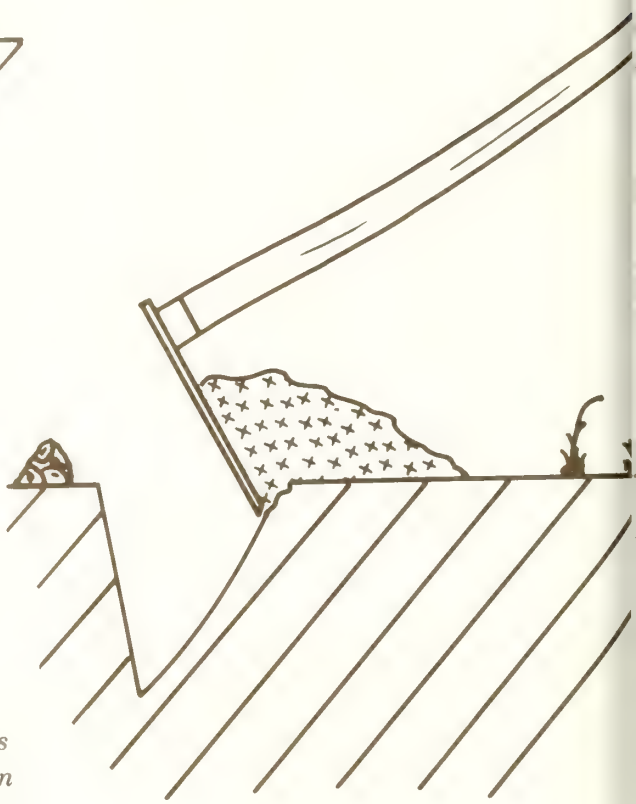
STEP 3

Swing mattock with sufficient force to bury blade to full length in one or two swings; leave blade in soil after final swing.



STEP 4

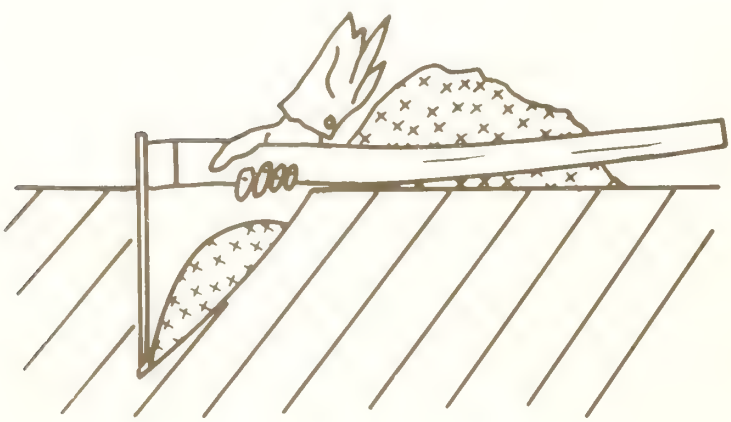
Lift handle sharply to break soil at bottom of hole.



STEP 5

Pull loosened soil into a compact pile near front of hole.

STOP. Do not plant if hole is not in mineral soil—duff, humus, and rotten wood dries rapidly and compacts poorly around roots.



STEP 6

Trim rear wall of hole to vertic
using a shortened grip on mattoc

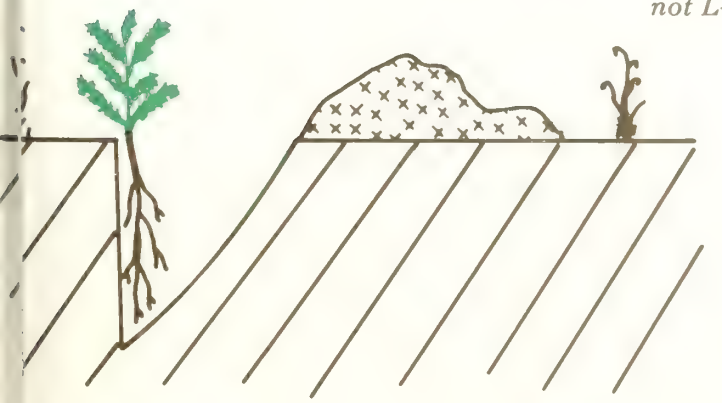
STEP 7

Grasp seedling stem near root collar—do not pull on foliage—and remove from tray or bag carefully to prevent tearing intertwined roots. Remove one tree only, and be sure that roots of seedlings in container remain covered. Do not expose seedling before hole is dug.

STEP 8

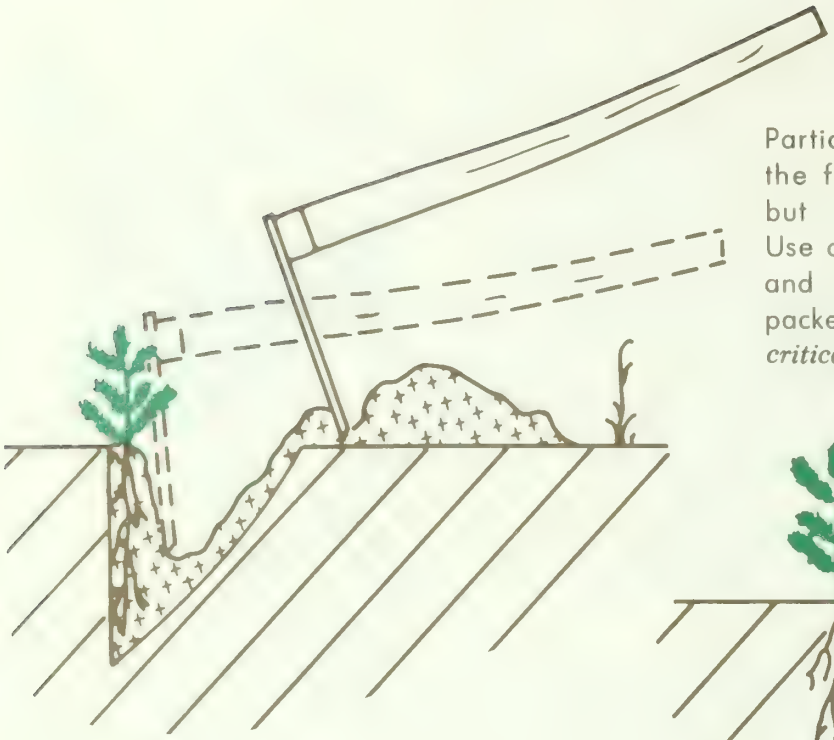
Spread roots against rear wall of hole with root collar at or slightly below ground level.

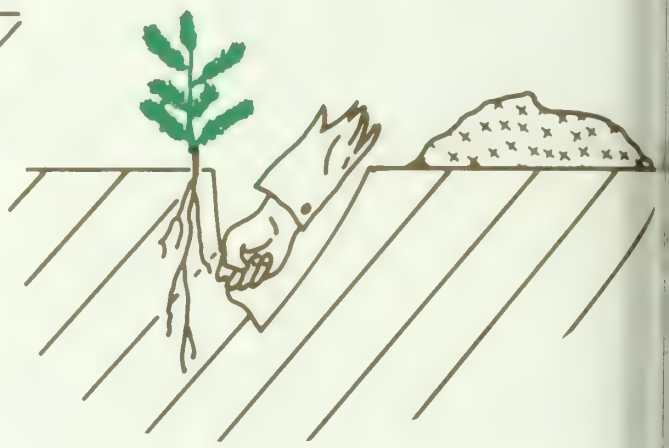
Be certain roots extend vertically and are not L-, J-, or U-shaped.

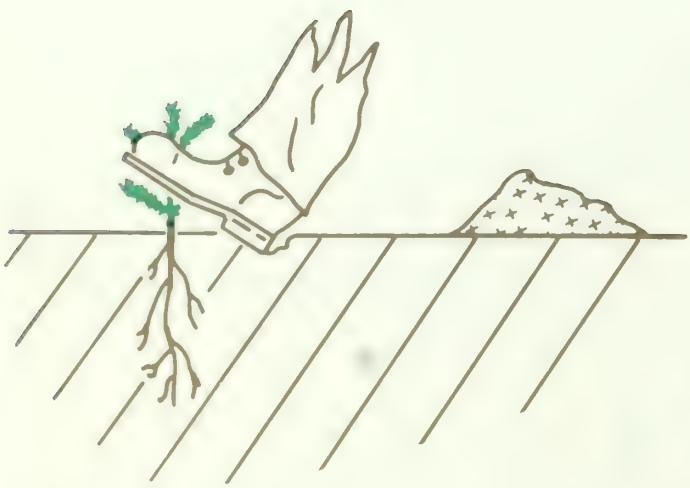


STEP 9

Partially fill hole with *moist* soil and, us
the fist or toe of the mattock, pack firn
but *carefully* to prevent injury to roo
Use only enough soil—freed of large sto
and any accumulated debris—to form
packed layer about 1 inch thick. *This step
critical for intimate soil-root contact.*







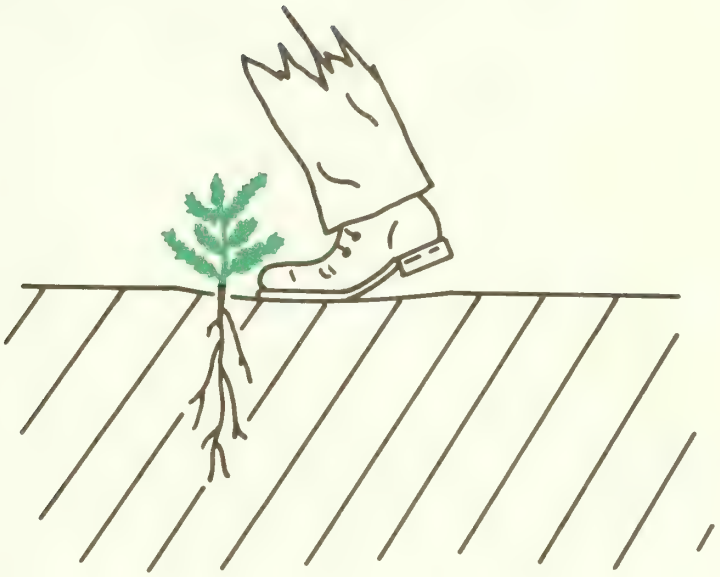
STEP 10

Fill hole with *moist* soil and pack firmly using the heel of the mattock or boot heel; usually three or four tamps are sufficient.

Soil is properly packed when tree cannot be pulled from hole easily.

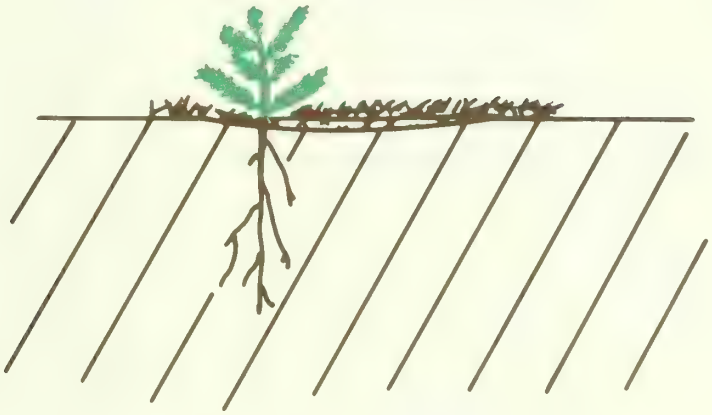
STEP 11

Fill deep depressions left by scalping or packing and firm soil around seedling.



STEP 12

Cover planting spot with a mulch of *loose* soil or litter to reduce evaporation. Whenever practical, arrange logs or slash for added protection against solar radiation (figs. 1A, 1B, 2D, 5).



Plantation Protection

During the juvenile stage, seedlings in plantations are exposed to many hazards which are more difficult to assess and eliminate than those encountered before planting. Nevertheless, these hazards must not be neglected if reforestation is to be successful. They include such environmental and biotic factors as frost, intense solar radiation, rodents, snow-mold fungi, and large animals.

In some instances these factors may be the immediate cause of mortality, but often seedlings are progressively weakened by several causal agents and subsequently die. For example, mortality was high in a newly established plantation when current growth was killed by summer frosts in 4 of 6 years, and part of the remaining foliage was killed by snow mold during 4 winters of the same period.

Most rodent injury of spruce seedlings is caused by mountain pocket gophers (Thomomys talpoides). Although some mortality is likely every year from girdling, severing the stem, or from burrowing activity, losses are highest during peak population years. Mice have been observed to girdle associated species extensively, but only scattered damage has been reported for spruce seedlings.

Information regarding the magnitude of large animal damage in spruce plantations is limited (Roe et al. 1970). Generally, grazing is not the immediate cause of mortality, unless seedlings are severed below live branches. The adverse effect of grazing is reflected by loss of seedling vigor; the photosynthetic capacity of seedlings is reduced as foliage is browsed. Spruce seedlings, because of their small size, are particularly vulnerable to trampling. Not only is photosynthesis reduced as branches are broken off, but the flow of nutrients and water is disrupted by crushed stem tissue, which may be severe enough to cause direct mortality. The worst feature of grazing is that it is repeated year after year, and when coupled with injury from other sources, the chances for survival are limited. Cattle appear to cause less damage to plantations than sheep, but successful plantations have been observed on sheep allotments where seedlings were protected by down timber.

Recommendations:

1. Avoid planting in frost pockets—temperatures are likely to be so severe that normal protective cover will not prevent injury.
2. Avoid planting in areas where advanced regeneration shows high incidence of snow mold.
3. Initiate a rodent survey program, and control animal when populations build up.
4. Grazing should be prohibited until seedlings reach height of at least 3 feet to prevent trampling damage. Light grazing could then be permitted providing concentrations of livestock can be avoided. If systematic observations disclose browsing damage then grazing should be discontinued until terminal buds are beyond reach of livestock.

Records

Adequate data from detailed records are needed to (1) correct deficiencies causing failure and (2) recognize good practices leading to successful plantations. Decisions affecting regeneration practices can then be based on quantitative information rather than conjecture.

The following recommendations are suggested for minimal records; individual preference or circumstances may justify others.

Recommendations:

1. Provide a record of plantation establishment: (1) location; (2) size; (3) species planted; (4) kind of stock (age, size, quality, or grade); (5) seed source; (6) planting dates; (7) method of site preparation and equipment used; (8) method of planting and kind of tool used; and (9) density of planting.
2. Maintain continuous thermograph record of temperatures during transit and local storage.
3. Use staked trees to obtain continuous detailed information:
   a. Stake at least 100 trees in small plantations, and 1.5-2.5 percent of total planted in large plantations.
   b. Staked trees should be alined across the direction of travel to sample variation due to planter.
   c. Staked trees should be alined roughly perpendicular to the contour to sample topographic variation.
4. Determine course of plantation establishment by recording survival at the end of the first, and the beginning of the second and third growing season.
5. Identify and record cause of mortality or injury to staked seedlings.
   a. Rodent girdling or severing of the stem can usually be identified (mice, gophers, or porcupines) by the relative size of incisor tooth marks left in wood tissue.
   b. Frost injury can be recognized within a few days after freezing by the limp, wilted appearance of current growth. The current foliage later turns a light tan or straw color, regardless of the stage of development of the shoot. Older foliage shows no visible injury.
   c. Solarization is most easily detected by the yellow or yellowish-green foliage—symptoms appear first in older foliage, but chlorosis is often evident in current growth by the end of the growing season.

Snow mold pathogens are readily identified by the dense, brown or brownish-black, mycelial mat formed over individual branches or entire seedlings. Drought injury can be recognized by the faded, light-green or blue-green needles which are dry and brittle, and usually drop off; undeveloped current-year shoots may wilt under severe dehydration. After the seedling has died, any remcining needles usually turn a dark, reddish brown within 7 to 10 days if soil moisture becomes available.

If seedlings show drought symptoms, the cause can sometimes be traced to improper planting—loosely packed soil or doubled roots.

Browsing damage by wildlife or livestock can often be determined by the frayed or splintered appearance of severed branches.

Trampling injury caused by large animals is evident from broken foliage and tracks near seedlings.

Record vigor of staked seedlings as poor, fair, good, or as otherwise desired, which can be used as a measure of plantation success along with survival data. Measure or estimate precipitation and general weather conditions for several weeks after planting.

Record, and most importantly, file data in such a manner that personnel not immediately involved with the specific plantation can use the information most effectively.

Summary

Spruce plantations can be established, but the job will not be easy. The task is not impossible, however, as recently demonstrated by operational plantings on the San Juan National Forest, if there is full realization that some of the planting operations can be lightly considered or haphazardly conducted. Satisfactory regeneration can be obtained, but planting costs will be higher than ever before, since many of the recommendations will increase supervision, require more specialized equipment, or lower daily production. Nevertheless, the cost will almost certainly be less than replanting.

Once the decision is made to reforest nonstocked land, emphasis must be placed on getting maximum survival rather than getting seedlings in the ground at the lowest cost. Cost accounting cannot be disregarded, but a more realistic method of evaluation must be applied, especially when regeneration is exceptionally difficult and costly. Consequently, success in spruce plantations should be measured by the amount invested for an established tree and not the commonly applied criterion of planting cost per acre.

Expected survival cannot be precisely predicted, because the impact of numerous environmental factors on newly established plantations varies from year to year. Studies indicate, however, that 75 percent of the planted seedlings can reasonably be expected to become established if catastrophic losses from factors such as gophers and snow mold can be prevented or avoided (Ronco 1970b).

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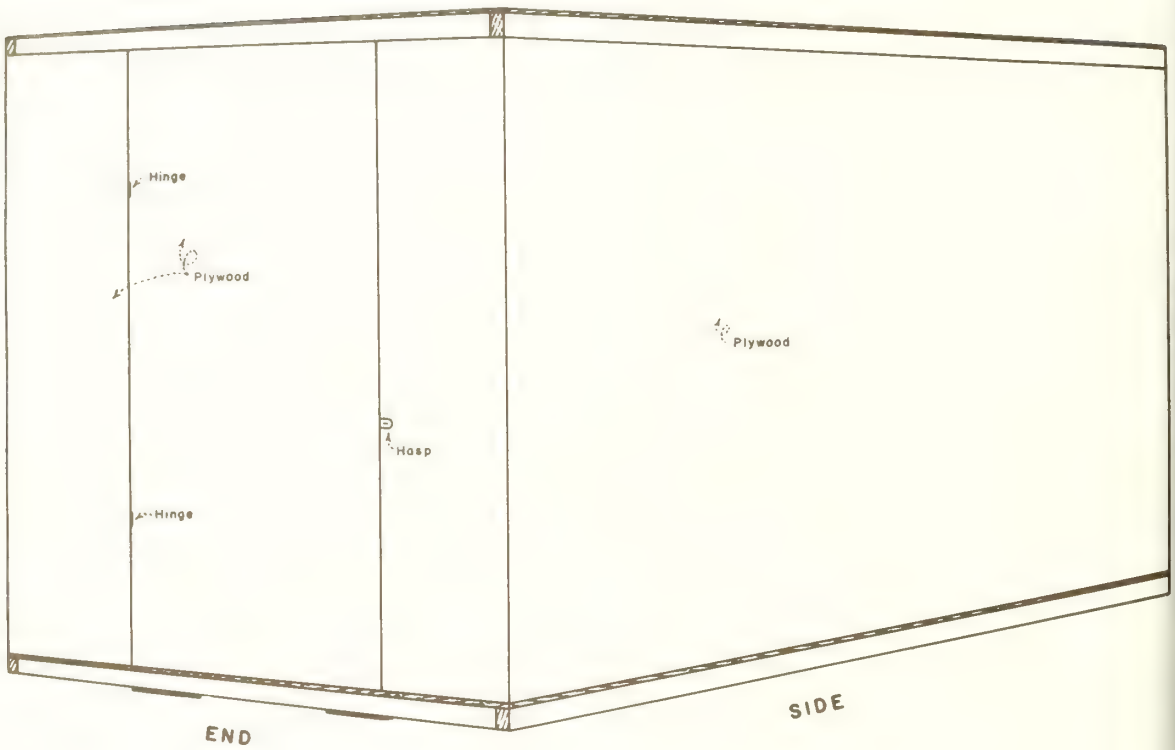
Appendix

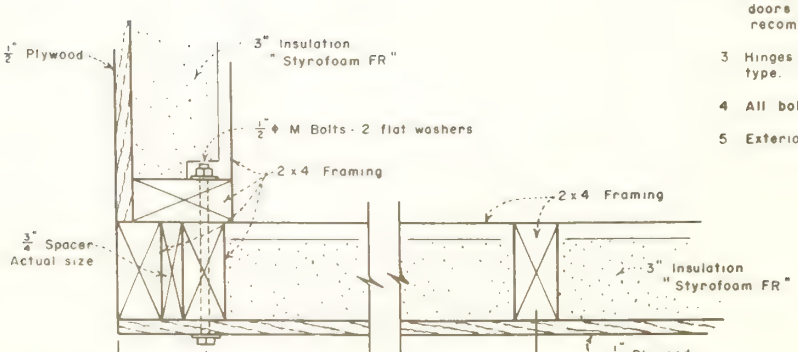
Construction plans for portable building used in Rocky Mountain Region, (Region Two), U. S. Forest Service for temporary cold storage of tree seedlings on the planting site.



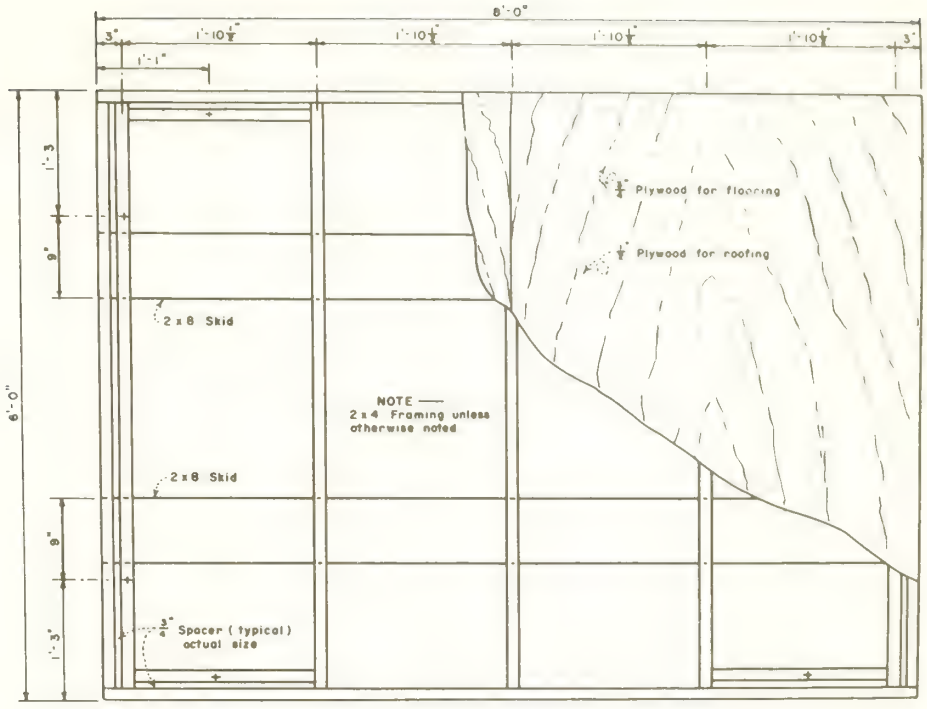
TREE STORAGE BUILDING

NOTES

1. All plywood shall be exterior grade.
2. Insulation shall be 3" thick, applied between framing on sid ends, roof and below flooring. Also to the $\frac{1}{8}$ hardboard c doors as shown in Section A-A. Adhered in place with odt recommended by the manufacturer.
3. Hinges shall be butt, loose pin type. Hasp shall be safety type.
4. All bolt holes to be drilled $\frac{1}{16}$" larger than bolts to be use
5. Exterior of building shall be painted white.



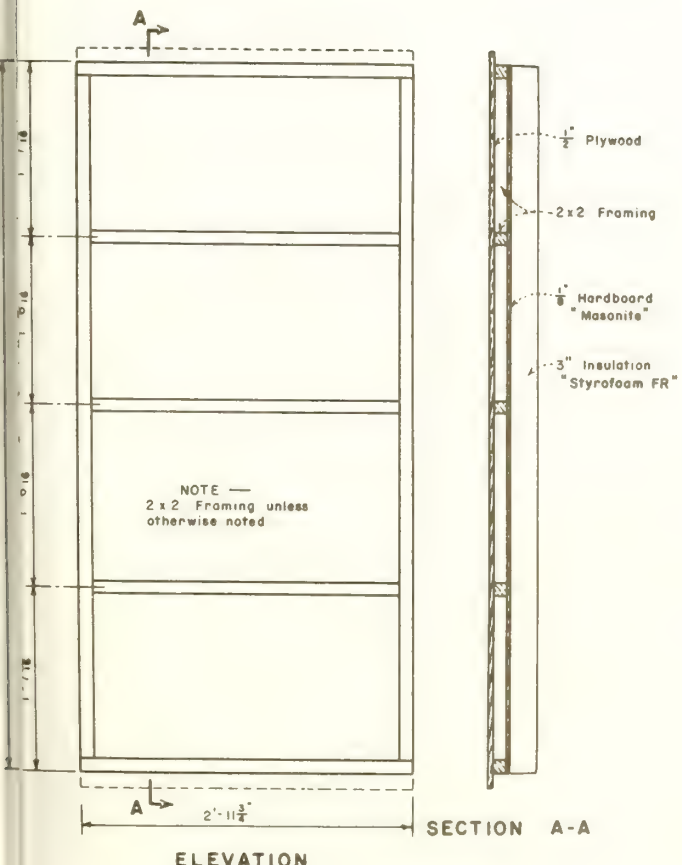
TYPICAL CORNER FRAMING
Scale 3" = 1'-0"



BASE PLAN - TYPICAL FRAMING

Scale 1" = 1'-0"

NOTE - The Top framing is similar as Base except ½" plywood used as roofing and 2 x 8 skids to be omitted.

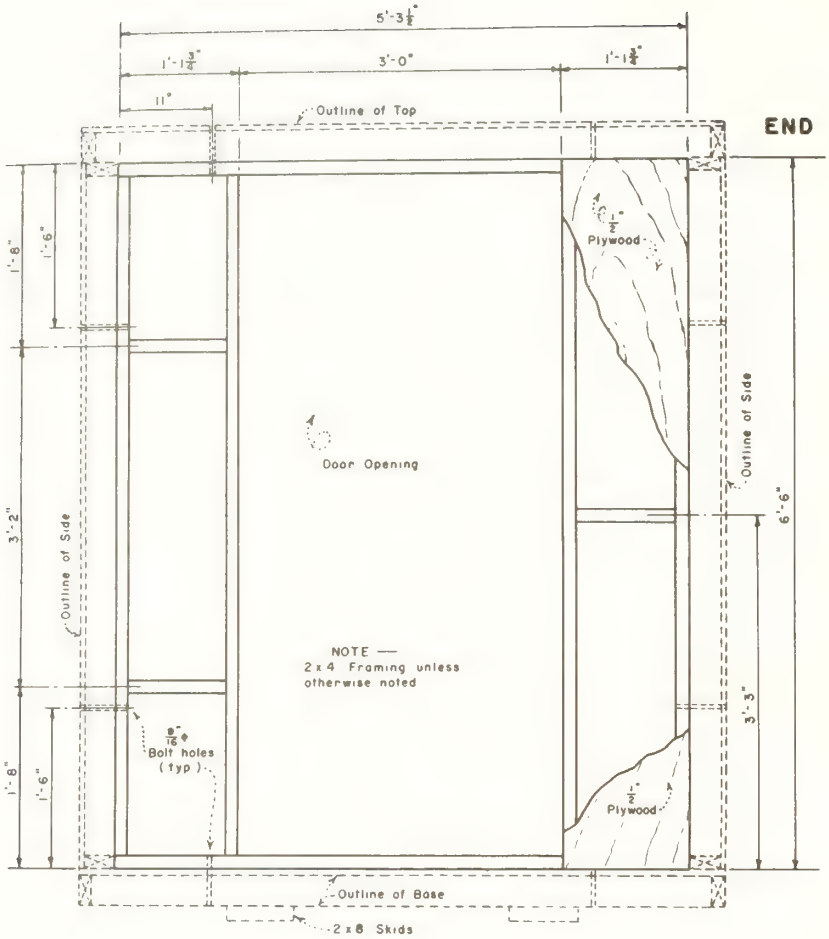


ELEVATION

SECTION A-A

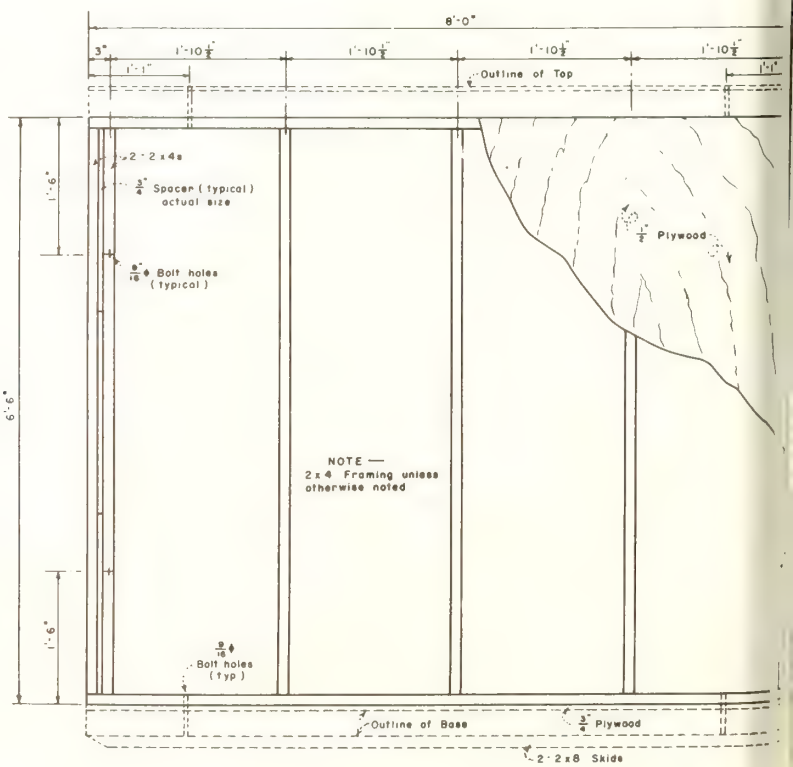
DOOR - TYPICAL FRAMING

Scale 1" = 1'-0"



END ELEVATION - TYPICAL FRAMIN

Scale 1" = 1'-0"



SIDE ELEVATION - TYPICAL FRAMING

Scale 1" = 1'-0"

Agriculture—CSU, Ft. Collins

Ronco, Frank.
1972. Planting Engelmann spruce. USDA For. Serv. Res. Pap. RM 89, 24 p. Rocky Mt. For. and Range Exp. Stn., Fort Collins, Colo. 80521.

Recommendations are provided to aid the forest manager in regenerating Engelmann spruce by planting in the central and southern Rocky Mountains. Reforestation operations covered include storage, transportation, microsite selection, site preparation, planting, plantation protection, and recordkeeping. The physiological and silvicultural requirements of spruces are discussed with respect to the harsh environment of the spruce-fir zone so that planting principles can be better understood.

Keywords: Picea engelmannii, planting, artificial regeneration.

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Frank Ronco

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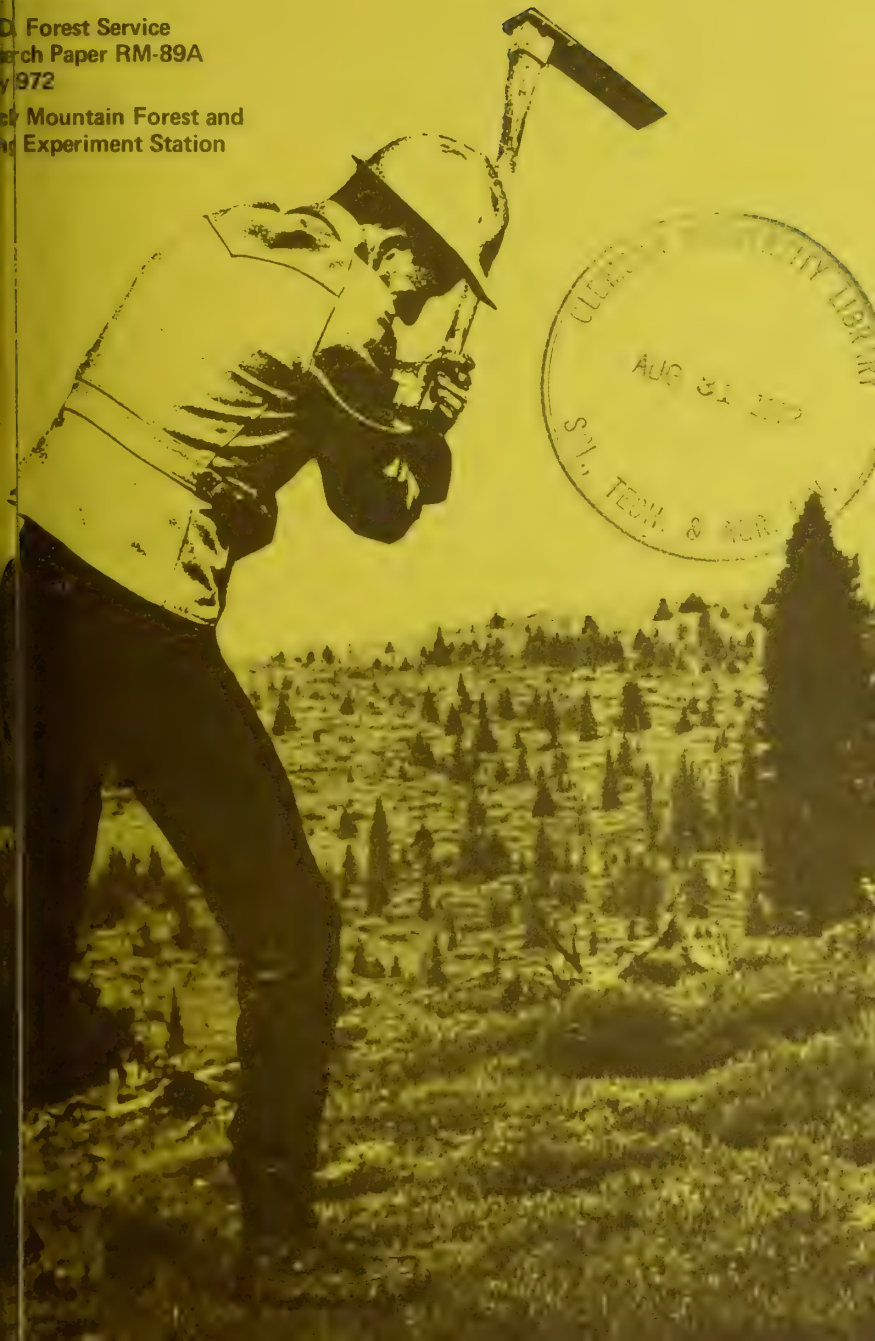
Mountain Forest and
Experiment Station



AUG 31

FOREWORD

This field guide was prepared to provide the planter with the techniques needed to establish Engelmann spruce seedlings successfully. Planting principles are discussed in detail in USDA Forest Service Research Paper RM-89, "Planting Engelmann Spruce," which emphasizes the relationship between the physiological and silvicultural requirements of spruces and the environmental conditions to which seedlings are exposed.

Rocky Mountain Forest and Range Experiment Station
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240 West Prospect Fort Collins, Colorado 80521

PLANTING ENGELMANN SPRUCE

A Field Guide

by

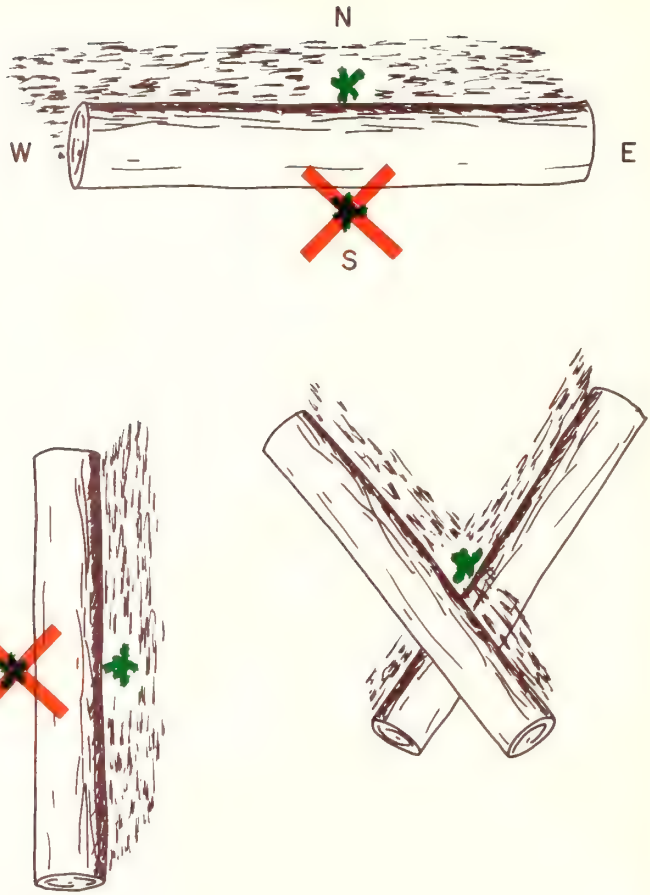
Frank Ronco

Engelmann spruce can be successfully planted in the Central and Southern Rocky Mountains! The job will not be easy, and in most instances it will cost more than planting other species, but it can be done. We have much of the basic knowledge and experience to carry out each phase of the planting operation successfully--stock production, storage, transportation, planting, and plantation protection. No plantation is likely to succeed, however, unless all phases are satisfactorily performed.

The need to control each operation adequately is more critical for spruce because of the harsh environment typical of most spruce-fir sites. After seedlings leave the nursery, they may be dehydrated, exposed to intense light, heated excessively, frozen in midsummer, attacked by disease, browsed, or trampled. This field guide was prepared to show the planter how to avoid or reduce the impact of those adverse factors. The relationship between the physiological and silvicultural requirements of spruce seedlings and their environment are discussed in detail in the companion Research Paper upon which this field guide is based.

SPRUCE SEEDLINGS NEED PROTECTION

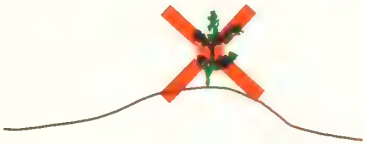
Spruce seedlings planted in the open generally do not survive very long. They are damaged by high light intensities--a process known as solarization--and die when exposed to full sunlight for prolonged periods. Open-grown seedlings are also exposed to temperature extremes. High temperatures increase water loss from both the plant and soil by transpiration and evaporation. Freezing temperatures, which occur during most growing seasons, kill nearly all current growth.



Logs, stumps, and slash provide suitable microsites f
planted seedlings if (1) planting spots are properly locat
alongside such cover, and (2) seedlings are placed close
enough (within 3 inches) to cover so that they are shaded.
Often, two logs can be crossed to create a new microsite
or improve an existing one by forming a "V" structure whic
offers maximum protection by shading a seedling on three
sides. Loose bark on stumps and logs, which can slip off
smother seedlings, should be knocked off with the planting
tool.

If dead material is not available, open cover of willows, tentilla, fireweed, or species of similar growth forms may used for protection. Dense, tall vegetation, however, as ll as small mounds or hummocks and depressions, are not od planting spots.

Silt smothers seedling



Soil dries out rapidly

Cured vegetation smothers seedling

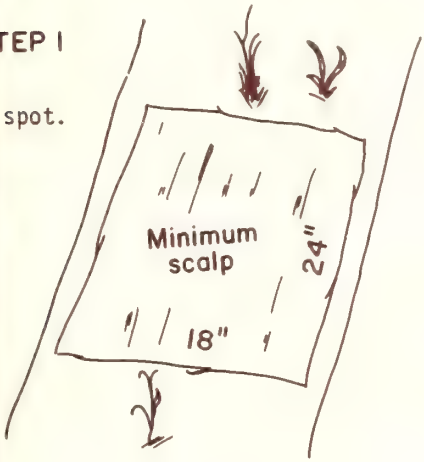
PLANTING SEASON

Spring is the best time to plant Engelmann spruce. The planting season is normally between May 25 and June 25, but it may be extended in some years because of late snowmelt. Planting after July 10, however, increases the risk of exposing seedlings to freezing fall temperatures before they become cold resistant.

REMEMBER! Seedlings are dormant, but living, when they are loaded at the nursery--keep them in this condition. Transport and store seedlings in facilities that are draft free, cool, and moist, but keep no more trees in temporary storage than can be planted in 1 week or less. Use refrigerators, insulated container units, cellars, or for a few days, even snowbanks. Work in areas sheltered from wind and direct sunlight when transferring seedlings to planting bags or trays. Continue care of trees during planting in a manner that duplicates, within practical limitations, good storage practices.

MATTOCK PLANTING

Since newly planted seedlings depend on existing root ystems for water uptake until new growth extends into un- apped moisture reserves, close contact between soil and oots is absolutely necessary. This can be accomplished est by using a mattock as a planting tool:

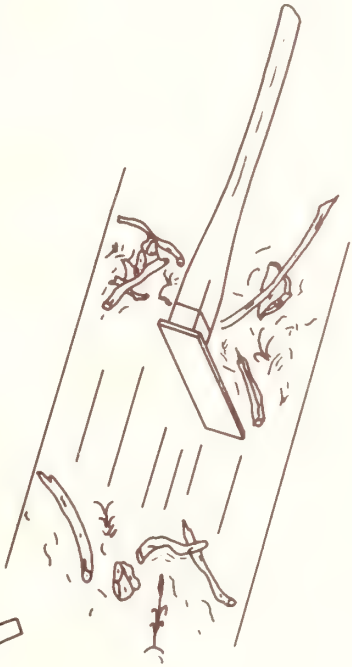


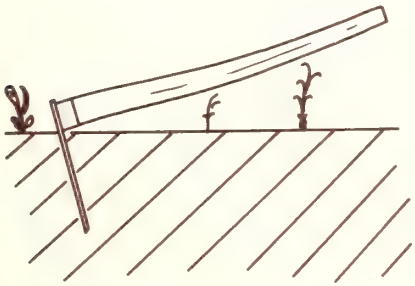
STEP I

ap spot.

STEP 2

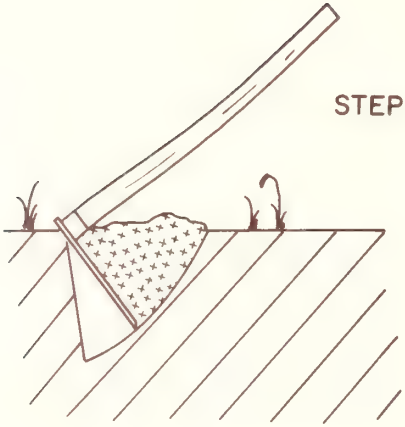
Scrape litter, dry soil, or other debris from spot.





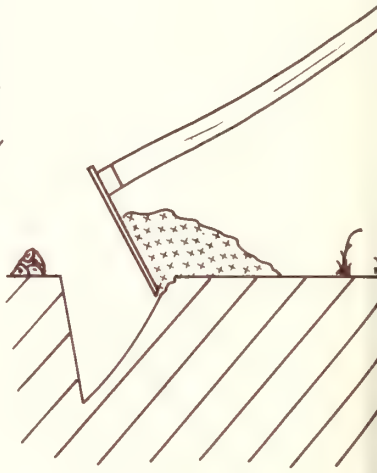
STEP 3

Sink mattock to depth of blade.



STEP 4

Lift handle sharply.



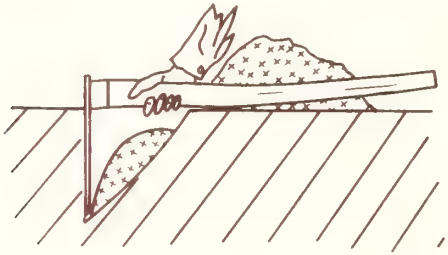
STEP 5

Pile loosened soil near hole.

STOP!

Skip hole if it is not

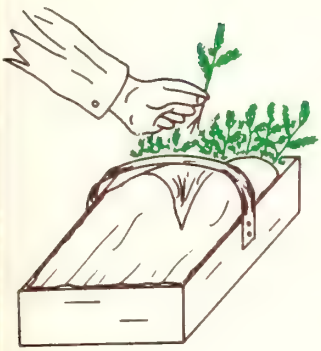
in mineral soil.



STEP 6

Trim rear wall of

hole to vertical.



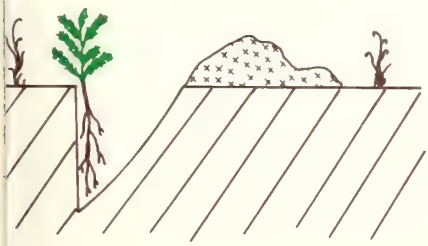
STEP 7

Gasp stem near root collar--

D NOT tear foliage or roots--

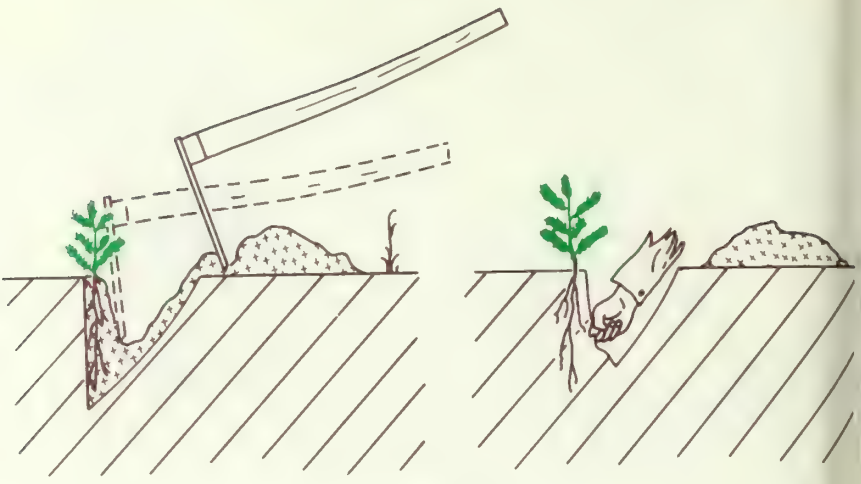
KEP container in shade and roots covered with wet moss-

D NOT expose seedling before hole is dug.



STEP 8

Spread roots against rear wall
with root collar at
or just below ground level--
DO NOT FORCE ROOTS INTO L-, J-
OR U-SHAPED POSITIONS.

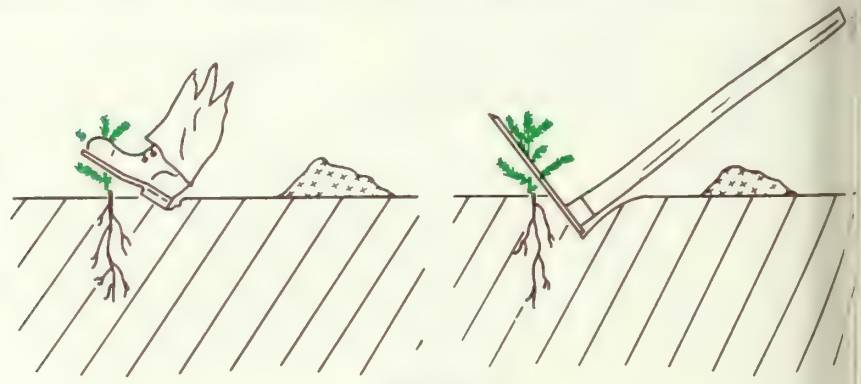


STEP 9

Pack about 1 inch of MOIST soil around roots with toe of mattock or by hand--

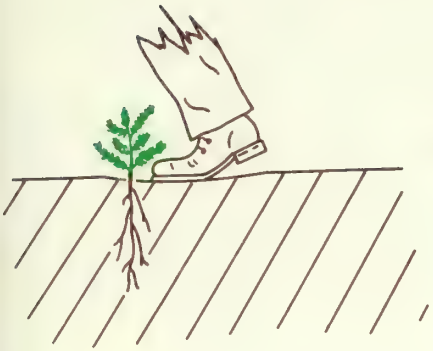
BE SURE SOIL IS FREE OF ROCKS AND LITTER.

ORM STEPS 9 AND 10 CAREFULLY TO PREVENT INJURY TO FOLIAGE AND ROOTS



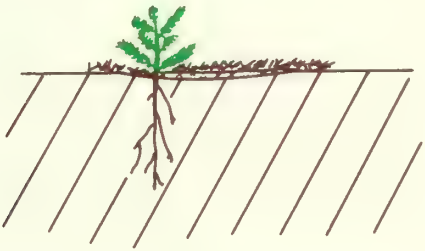
STEP 10

Fill hole with MOIST soil and pack TIGHTLY with heel of mattock or boot.



STEP 11

Level depression and firm soil.



STEP 12

Mulch spot with LOOSE soil or litter.

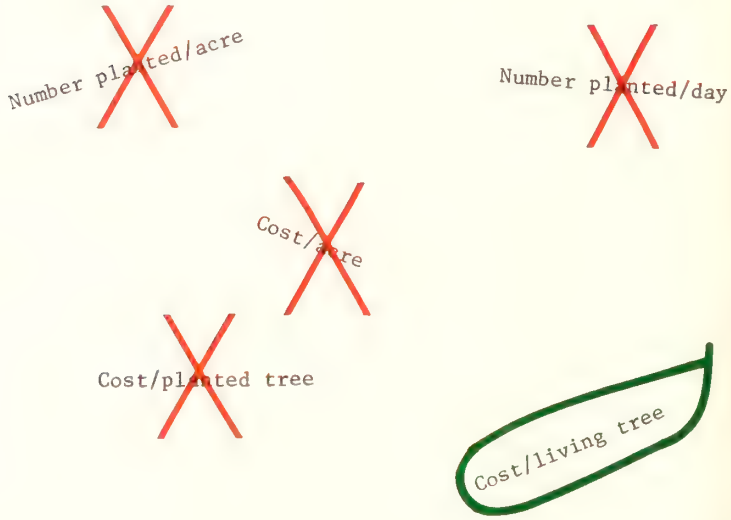
FOLLOW THROUGH AFTER PLANTING

The reforestation project is not completed when the last seedling is planted! An adequate number of seedlings for a representative sample of planter and topographic variation should be staked. Survival data and causes of injury or mortality should be recorded at the end of the 1st, and the beginning of the 2nd and 3rd growing seasons to measure success and identify potential risks to plantations.

Plantations must be protected against trampling by livestock until trees are at least 3 feet tall to avoid serious damage. Grazing may then be permitted, but plantations should be watched closely. If browsing damage occurs, terminate grazing until terminal buds are beyond reach of animals. Rodent populations, particularly pocket gophers, must be regularly censused, and control action taken when animal numbers begin to increase during the buildup phase of the population cycle.

MEASURING SUCCESS!

The number of surviving seedlings is the only true indicator for judging regeneration success!



SYMPTOMS OF

COMMON CAUSES OF INJURY AND MORTALITY

Rodent - The incisor tooth marks on girdled or severed stems can be related--by increasingly larger size--to mice, gophers, or porcupines, respectively.

Frost - Shoots of current growth appear limp and wilted within a few days after freezing. Current foliage later turns a light tan or straw color, regardless of the stage of development of the shoot. Older foliage shows no visible injury.

Solarization - Most easily detected by yellow or yellowish-green foliage; symptoms appear first in older foliage, but chlorosis is often evident in current growth by the end of the growing season.

Snow Mold - Brown or brownish-black mycelia of the fungi form dense mats over individual branches or entire seedlings; infected portion of seedling usually is dead.

Drought - Needles are a faded light green or blue green, are dry and brittle, and are usually retained on branches for some time. Incompletely developed, current-year shoots may wilt under severe dehydration. Dead needles that remain attached usually turn a dark reddish-brown within 7-10 days if soil moisture becomes available. Sometimes seedling death can be traced to desiccation resulting from planting error--loosely packed soil or doubled roots.

Browsing - The severed tissue of the stem on remaining branches is generally frayed or splintered.

Trampling - The stem or branches are broken, but usually are not separated. Animal tracks are also evident.

A. Forest Service
arch Paper RM-90
1972

y Mountain Forest and
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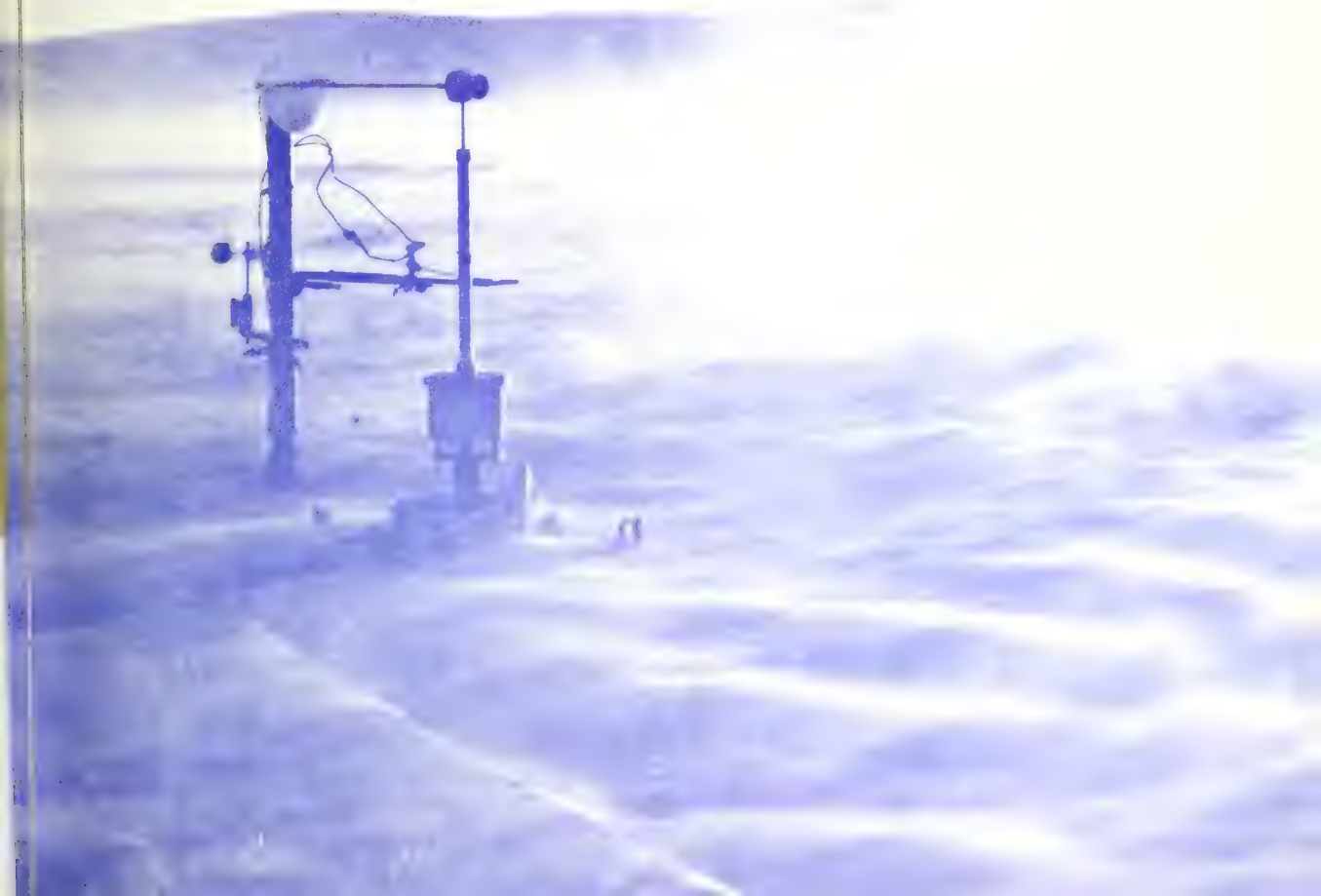
Department of Agriculture

Collins, Colorado

SUBLIMATION OF WIND-TRANSPORTED SNOW - A MODEL

by R. A. Schmidt, Jr.

AUG 31 1972
S.L. TECH. & ACQ. DIV.



ABSTRACT

Sublimation from blowing snow is estimated from the balance of heat and mass transfer on a volume of air and nonuniform ice particles. Size and the distribution of sizes are important particle factors, but fragmented and abraided shapes appear to increase sublimation only slightly above the estimate for spherical particles. Humidity and temperature are the overriding environmental factors, but atmospheric pressure and solar radiation are also important. The effect of turbulence on convection around the particles does not appear important in view of the small particle sizes encountered. Rather, turbulent transfer determines the snow concentration profile, and the gradients of heat and water vapor necessary to balance the sublimation process.

Keywords: Snow density, snow samplers, weather control, evaporation, sublimation.

USDA Forest Service
Research Paper RM-90

May 1972

Sublimation of Wind-Transported Snow — A Model

by

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Rocky Mountain Forest and Range Experiment Station[1]

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Sublimation of Wind-Transported Snow - A Model

R. A. Schmidt, Jr.

Although a small process in the total hydrologic cycle, sublimation of solid precipitation during redistribution by wind may be a significant part of the water balance in certain regions. The objective of this work is to formulate a mathematical model to estimate the mass of snow that returns to vapor as the air-snow mixture moves downwind over a horizontal snow surface. [2]

Following a brief description of the phenomenon, sublimation of snow is considered in three parts. **Part I** uses an existing equation for sublimation of an ice sphere to evaluate the effects of meteorological factors, and a modification demonstrates the influence of particle shape. **Part II** shows that natural snow concentrations are not large enough to cause significant particle interaction, so that the results of Part I apply to a cloud of snow particles as well. **Part III** combines this knowledge with expressions for the vertical gradients of windspeed, snow concentration, temperature, and humidity, to estimate sublimation from a vertical column above a horizontal surface. Discussion of this model leads to several interesting consequences which should be grounds for fruitful experimentation.

The title employs "sublimation" to describe the process under discussion. Although sublimation can be used to denote either deposition or vaporization, the phase change from solid to vapor is of primary concern here. The process is assumed to be quasi-stationary, and sublimation estimates are instantaneous values that do not take into account the change in surface area of the particles as the process proceeds. Philip (1964) has shown that, while not fundamentally correct, such analysis provides useful approximations for many meteorological problems. Calculations are included both to provide more meaning to the equations and to given values that help keep the numerous factors in their proper perspective. In most cases, these results are presented graphically. The symbols are defined as they are introduced, and are listed in the appendix for reference.

The fact that the snow particles vaporize, either partly or sometimes completely, during transport by wind is not directly observable, since measurement problems are not yet solved, even for the relatively simple situation of transport across a horizontal surface. At windspeeds sufficient to move snow, natural airflow is turbulent, and windspeed increases with height. Snowflakes formed during precipitation are quickly reduced toward spherical shapes by mechanical abrasion, so that the windblown particles become like sand. As a particle leaves the snow surface to become suspended in the turbulent air stream, a boundary layer develops around it. If the vapor pressure of water in the surrounding atmosphere is different from the saturation value, a vapor pressure gradient forms across the boundary layer and sublimation begins. The rate of the process depends on how rapidly air is exchanged in the particle boundary layer. Energy, in the form of heat, is transferred to or from the particle surface by conduction, convection, and radiation. Water vapor is transferred by diffusion and convection. These same mechanisms operate in a cloud of snow particles, since the interparticle spacing far exceeds the depth of particle boundary layers under natural concentrations of snow suspended in turbulent air.

[2] *My initial interest in this problem was generated by discussions with R. D. Tabler. M. D. Hoover and M. Martinelli, Jr. helped at each stage of the development. J. L. Kovner and U. Radok reviewed the manuscript with great insight.*

PART I
SUBLIMATION OF A SINGLE PARTICLE

A. An Ice Sphere

Two laws of physics provide the starting point for theoretical considerations of the sublimation process. Conservation of mass provides a relationship in the form of the diffusion equation. The relationship for heat transfer comes from the law of conservation of energy.

1. Diffusion and Conduction

For mass transfer, the classical approach (Houghton 1933) is based on the differential equation relating the rate of loss of mass (dm/dt) of a spherical particle (radius r) to the surface area of the particle, the diffusivity (D) of water vapor in air, and the vapor pressure difference at the particle surface. The resulting equation for evaporation of a sphere in still air is

$$(dm/dt) = 4\pi Dr(\rho_\infty - \rho_r) \qquad [1]$$

where ρ_∞ is the water vapor density in the remote environment and ρ_r is the value at the particle surface. This equation expresses the rate of sublimation (or condensation) of a spherical particle by diffusion without ventilation.

Heat transfer by conduction to a sublimating spherical particle depends on the surface area, the temperature difference, and the thermal conductivity of air, K. The expression is

$$L_s\,(dm/dt) = 4\pi Kr(T_\infty - T_r) \qquad [2]$$

where L_s is the latent heat of sublimation. Temperature in the remote environment is T_∞ and T_r is the surface temperature of the particle.

2. Convection

When a spherical particle sublimates in a steady air stream, the rate is higher and mass transfer varies around the particle surface. Frössling (1938) predicted this pattern from boundary layer theory, and verified his calculations with measurements of mass transfer around a naphthalene bead. The rate was maximum on the exposed face of the sphere, and decreased to a minimum at the point where the boundary layer separated from the particle surface. A smaller maximum occurred in the "eddy" area on the downstream surface. Temperature differences measured by Ranz and Marshall (1952) show a similar pattern around a ventilated drop.

Both Frössling (1938) and Kinzer and Gunn (1951) introduce "wind factors" by which the righthand sides of [1] and [2] are multiplied to account for increased sublimation due to ventilation. These ventilation factors are related by boundary layer theory to the particle Nusselt number (Nu) = 2rK/D for heat transfer and to an analogous ratio for mass transfer, the Sherwood number (Sh), often denoted by (Nu') in the literature. Thus, the theoretical equations are

$$(dm/dt) = 2\pi Dr\,(\rho_\infty - \rho_r)\,(Sh) \qquad [3]$$

$$L_s(dm/dt) = 2\pi Kr(T_\infty - T_r)(Nu) \qquad [4]$$

where (Sh) and (Nu) must be determined by experiment. Theory predicts, however, that (Nu) is a function of Reynolds number (Re) = 2rV/ν and Prandtl number (Pr) = $C_p\mu/K$, while the analogous Sherwood number is a function of (Re) and the Schmidt number (Sc) = $\mu/\rho_a D$. In these dimensionless groups V is the ventilation velocity, μ is the dynamic viscosity, ρ_a is the density, and C_p is specific heat, all for air in this case. The kinematic viscosity is $\nu = \mu/\rho_a$.

At this point, the Clausius-Clapeyron equation $(1/P_s)(dP_s/dT) = L_sM/RT^2$ may be used to approximate the water vapor density difference in [3], where P_s is the saturation vapor pressure, M denotes the molecular weight of water, and R is the universal gas constant. Thorpe and Mason (1966) show that [3] and [4] may be combined to give the following expression for sublimation rate of a spherical ice particle:

$$\frac{dm}{dt} = \frac{2\pi r\,(\rho_\infty/\rho_{sT} - 1)}{\dfrac{L_s}{KT}\dfrac{1}{(Nu)}\left\{\dfrac{L_sM}{RT} - 1\right\} + \dfrac{1}{D\rho_{sT}\,(Sh)}}$$

where ρ_{sT} represents the saturation density of water vapor at temperature T. The quantity $(\rho_\infty/\rho_{sT} - 1)$ is the undersaturation of the environment with respect to water vapor, and, following their notation, is denoted by σ.

Results of their experimental work with ice spheres ($0.3\ mm \leq r \leq 1.8\ mm$) at ventilation speeds from 25 to 100 cm sec^{-1} show that the Nusselt number and the Sherwood number are practically the same, and are proportional to the square root of the Reynolds number.

$$(Nu) \simeq (Sh) = 1.88 + 0.58\,(Re)^{1/2} \qquad [5]$$

where (Re) ranged between 10 and 200. Values

f D in their computations are about 7 percent ower than the International Critical Tables alue, in keeping with the experience of other orkers, for example, Ranz and Marshall (1952).

Mean ventilation velocity, V, is the average elative velocity of air with respect to the article. In these experiments, particle position as fixed in a moving air stream of low turulence intensity (1 to 3 percent). The wind actor, F, by which sublimation is increased ue to convection, has a theoretical value of nity when the Reynolds number is zero. However, [6] provided the best fit to their experimental data, so that $F = 1/2\ (Nu)$ is slightly ess than unity with no ventilation. Ventilation nay increase the diffusion of water vapor from he ice sphere by as much as five times if article Reynolds numbers as high as 200 are nvolved (fig. 1).

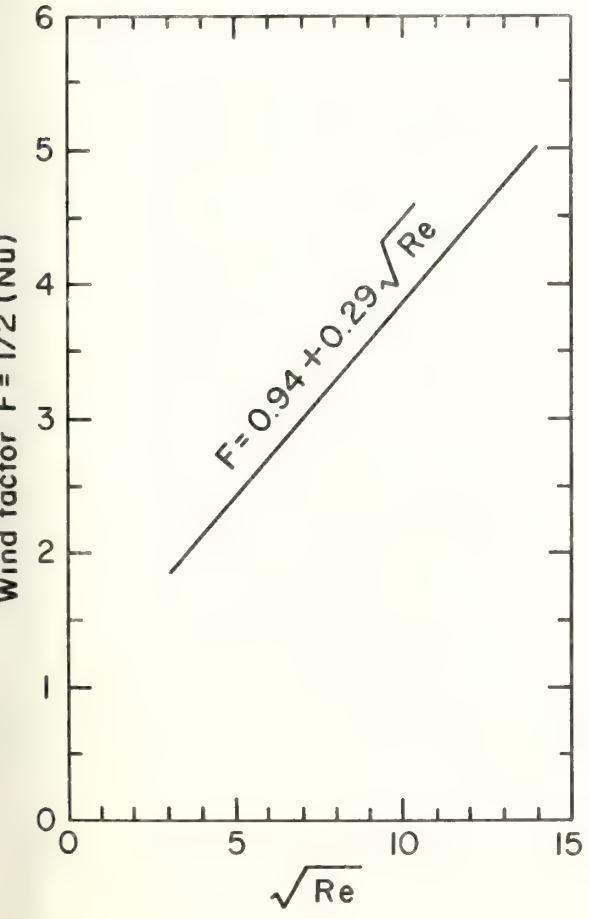


Figure 1.--Experiments by Thorpe and Mason (1966) show that ventilation increases sublimation by a factor (F) proportional to the square root of the Reynolds number, where (Re) = (2rV/ν) ranged from 10 to 200.

3. Particle Temperature

For water drops evaporating in still air, measurements by Johnson (1950) confirm the relation $(T_r - T) = (DL_s/K)(\rho - \rho_r)$. This expression for the temperature difference between the particle and its environment comes from assuming steady state equilibrium of heat and mass transfer expressed by [1] and [2]. Multiplying [1] by L_s gives an expression equivalent to [2]. In practice, the value of ρ_r is taken as the saturation vapor density at particle surface temperature T_r. The value of ρ, the ambient vapor density, is determined from the relative humidity of the environment and its temperature T.

Direct measurements by Kinzer and Gunn (1951) and Ranz and Marshall (1952) show that, for practical purposes, the surface temperature of a water drop evaporating with ventilation is equal to the wet bulb temperature estimated from psychrometric tables. Kinzer and Gunn (1951) also found the temperature of suddenly ventilated drops adjusted to the wet bulb temperature in only a few seconds.

For this model, particle temperatures are assumed to equal ice bulb temperatures. In the temperature range from -20° C. to 0 ° C., $(T_r - T)$, taken as the ice bulb depression, is less than 0.5° C. for relative humidities greater than 70 percent over the elevation range 0 to 4 km. Thorpe and Mason (1966) assumed the temperature difference $(T_r - T)$ was so small for conditions below freezing that the saturation vapor density at the particle surface was taken as that for ambient temperature T. Thus, particle temperature does not enter directly in [5].

4. Calculations

Together, [5] and [6] provide sublimation rates for ice spheres under conditions of moderate ventilation, at temperatures below freezing, without considering the radiation of heat to the particle. Some calculations will provide a graphical picture of the relation between factors. Before calculations can be made using [5], however, a number of "constants" must be assigned values. This has been done in the tables in the appendix.

Figure 2 shows the sublimation rate as a function of particle diameter for several ambient temperatures and mean ventilation velocities. All values were computed for 1000 mb atmospheric pressure, and 90 percent relative humidity. The sublimation rate at -10° C. is almost twice

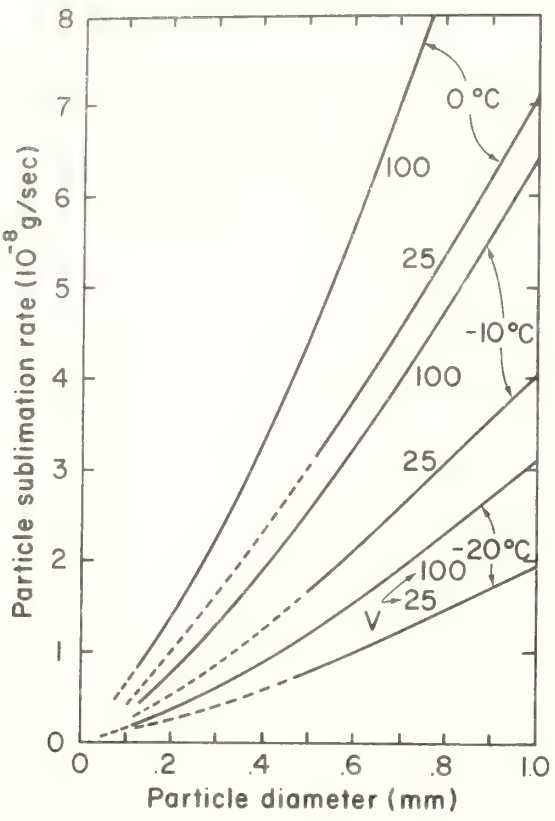


Figure 2.--The sublimation rate of a single ice sphere almost doubles for each 10-degree increase in ambient temperature between -20° C. and 0° C. Ventilation rate (V in cm/sec) has a smaller effect, according to equation [5] with values at 1000 mb. and 90 percent vapor density with respect to saturation over ice. (The dashed portion of the curves are extrapolations below (Re) = 10.)

the rate at -20° C. throughout the size range, and more than doubles when sphere diameter is doubled. Examination of [5] reveals that sublimation is directly proportional to the water vapor deficit in the surrounding environment. Doubling this undersaturation doubles the sublimation rate; 80 percent relative humidity would give twice the sublimation rates shown in figure 2.

Rate of sublimation decreases for smaller particles, but the loss becomes a larger percentage of particle mass. This follows from equations [5] and [6], which predict that sublimation rate varies as the 3/2 power of particle radius, and the fact that total particle mass varies with the third power of radius (fig. 3).

Particles studied by Thorpe and Mason were larger than most windblown snow. Budd, Dingle, and Radok (1966) reported mean particle diameters near 100 μ in the Antarctic, and Kojima (1969) presented particle size distributions with modes in the 20-40 μ diameter class, measured at Hokkaido University, Japan. Measurements on water drops by Kinzer and Gunn (1951) showed a rapid decrease in mass transfer for diameters below 150 μ when the relative velocity was equal to drop fall velocity. They point out that fog and cloud-size drops (around 25 μ) evaporate at about the rate predicted for a drop at rest. At low Reynolds numbers (0 to 7), the mechanism is not completely known, but air is apparently entrained by viscous forces and the drop tends to evaporate into an air shell around it. (Radius of curvature does not exert an important influence on vapor pressure, for particles larger than 1 micron.)

Perhaps the best limit to use in applying equation [5] to small particles is (Re) = 10, the lower limit given by Thorpe and Mason (1966) which agrees with the arguments of Kinzer and Gunn (1951). A 100 μ particle ventilated by a 100 cm/sec air stream at -20° C. (Re = 8.6) is slightly outside this limit. With 90 percent relative humidity and 1000 mb atmospheric pressure, equation [5] predicts the sublimation rate will be $1.5 \cdot 10^{-9}$ g/sec.

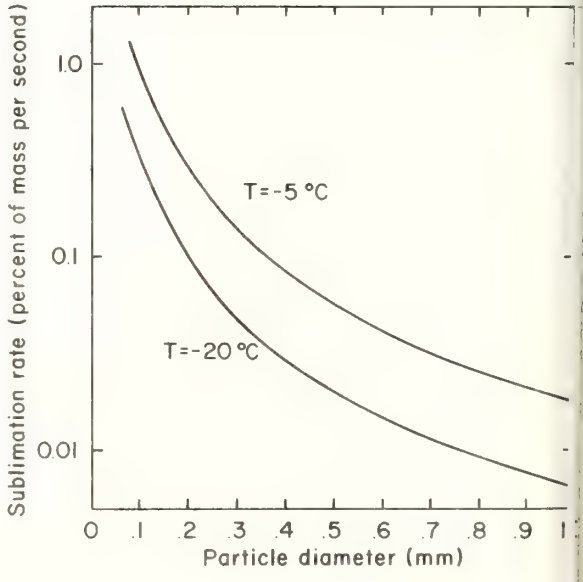


Figure 3.--The sublimation rate calculated by equation [5] represents a much larger percentage of the total mass for small particles. Calculations plotted here are for 1000 mb pressure and a vapor density that is 90 percent of the saturation value over ice. Particle density is assumed to be 0.92 g/cm^3.

5. Radiation

For laboratory studies, most experimenters have justified neglecting heat transfer by radiation as part of the sublimation or evaporation process. However, Bergen [3] shows this factor is important for sublimation of a snowflake under solar radiation. Since redistribution of snow by wind may occur with clear skies, radiation will be included in this model. Following Bergen's procedure, a term is added to the heat transfer relation [2] so that

$$L_s(dm/dt) = 4\pi Kr(T_r - T) + Q \qquad [7]$$

where Q is the net rate at which heat is transferred to the particle by radiation. If the heat transfer expression [7], with the radiation term, is used in place of [2] to derive the equation for particle sublimation rate by the argument of Thorpe and Mason (1966), the result is

$$\frac{dm}{dt} = \frac{2\pi r\sigma(Nu) - \frac{Q}{KT}\left(\frac{L_s M}{RT} - 1\right)}{\frac{L_s}{KT}\left(\frac{L_s M}{RT} - 1\right) + \frac{1}{D\rho_{sT}}} \qquad [8]$$

To evaluate Q, some expression for the total radiation balance on the particle must be formulated. This will certainly be a widely varying term since conditions range from clear nights to clear days, with all cloudy and foggy situations between.

According to definitions outlined by van de Hulst (1957), a particle causes extinction of incident radiation equal to the amount it scatters and absorbs. Scattered radiation includes that defracted, refracted, and reflected by the particle. Of the incident radiation flux, S_o, the portion absorbed by the particle is equal to $C_{abs}\ S_o$, when C_{abs} is an area defined as the absorbing cross section of the particle. An absorbing efficiency may also be defined so that $E_{abs}=C_{abs}/G$ where G is the particle's geometric cross section ($G = \pi r^2$ for a sphere). If ζ is the particle albedo, $E_{abs} = 1 - \zeta$.

The total radiation flux intercepted by a spherical particle, suspended in turbulent air above a horizontal snow surface, will be taken as the sum of direct and scattered solar radiation. If S_o is the total solar radiation flux from above, and λS_o is that portion reflected by the horizontal snow surface, then the total radiation load on the particle is $S_o + \lambda S_o$, where the horizontal surface albedo, λ, may be different from the particle surface albedo. The amount of this incident flux absorbed by the particle is $C_{abs}(S_o+\lambda S_o)$, or $E_{abs}G(S_o+\lambda S_o)$. It is equal to Q, the net rate of radiant heat transfer to the particle, and with $E_{abs} = 1 - \zeta$ and $G = \pi r^2$, for a spherical particle

$$Q = (1 - \zeta)(1 + \lambda)\pi r^2 S_o \qquad [9]$$

Values of albedo for a horizontal snow surface range from 75 percent or less for old snow, to almost 100 percent for new snow surfaces (Geiger 1965). A conservative value of $\lambda = 0.8$ has been used in calculations below. No estimates of snow particle albedo could be found in the literature, and a calculation based on particle optics was not formulated because no assumed surface characteristics seemed well founded. Instead, the value $\zeta = 0.5$ was taken as a very rough estimate.

This analysis neglects thermal radiation from the horizontal surface to the particle, because large differences between surface and particle temperatures do not seem likely under the natural conditions considered here. When snow is transported by wind just above asphalt, or a bare soil surface, thermal radiation might become an important additional heat flux to the particle.

Figure 4 compares sublimation rates computed from [8] and [9] with rates predicted by [5]. Most obvious is the fact that radiation contributes more in sublimation from large particles. The sublimation rate by [8] and [9], with $S_o = 1.0$ cal/cm^2 min, is 18 percent larger than when radiation is neglected for a 100 μ sphere, and 84 percent larger for a 1 mm diameter sphere.

6. Atmospheric Pressure

Rates of sublimation at different elevations may be compared by evaluating [5] and [8] for the corresponding ambient pressures. Only two parameters in equation [5] vary significantly with pressure. Ventilation factors change due to the variation of the kinematic viscosity, and diffusivity of water vapor increases with decreasing pressure.

Variations in kinematic viscosity were estimated from the defining relation $\nu \equiv \mu/\rho_a$ where μ, the absolute viscosity of air, is almost independent of pressure. The density of the air was taken as $\rho_a = p/C_v R T_v$ where p is the pressure, C_v is the coefficient of compressibility, R is the gas constant and T_v is the virtual temperature (List 1968). The results (included in the appendix) show that Reynolds number, and thus the ventilation factor [6], decrease with decreasing pressure. The variation in diffusivity with pressure is $D/D_o=(T/T_o)^n(p_o/p)$,

[3] *Bergen, James D. An estimate of sublimation losses due to redeposition. Unpublished semiannual report of watershed management research, 1966. Rocky Mt. Forest and Range Exp. Stn., Fort Collins, Colo.*

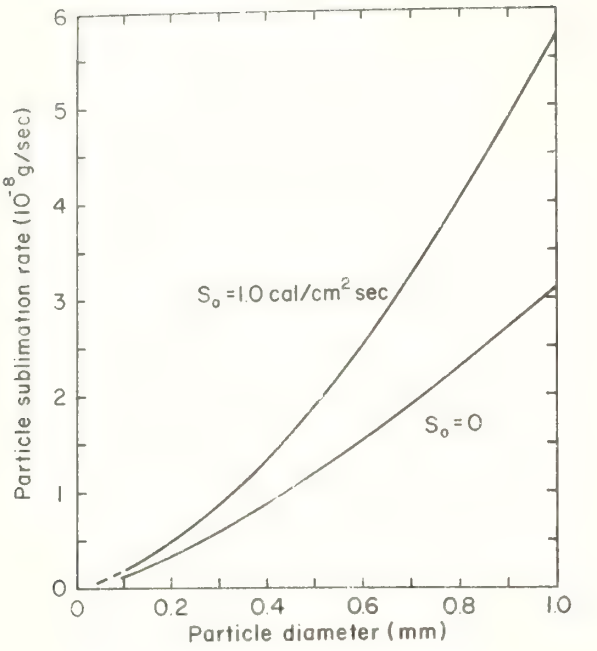


Figure 4.--Solar radiation is more effective in increasing the sublimation rates of larger particles, according to this evaluation of equations [8] and [9] for -20° C. at 1000 mb. The vapor density was 90 percent of the saturation value over ice, and a ventilation rate of 100 cm/sec was assumed for all sizes. The particle surface albedo was taken as $\zeta = 0.5$ and the horizontal surface albedo as $\lambda = 0.8$ in equation [9].

where D_o is 0.180 cm^2 sec^{-1} at p_o = 1000 mb (List 1968). Computations in the appendix are for a temperature of -20° C.

The change in the computed sublimation rate over the elevation range from 0 to 4 km (0 to 13,000 feet) is compared for two particle sizes in figure 5. Substantial increases in sublimation rate are predicted for higher elevations, and the increase is more significant for smaller particles. The increase in diffusivity outweighs the reduction in ventilation rate due to decreased density of air at higher elevations.

Besides changes in ventilation factor and diffusivity, comparisons employing equation [8] must account for the increase in direct and diffuse solar radiation at higher elevations. The mean radiation flux increases by two to three times between sea level and an elevation of 4 km (Geiger 1965). Figure 6 compares sublimation rates at sea level (1000 mb) with those at 2.5 km (750 mb) and 4 km (600 mb). Estimates of S_o, the radiation flux, are listed with the corresponding atmospheric pressure.

Of course, holding temperature and humidity constant over this elevation range is not realistic, but figure 6 does show that the net effect of decreasing atmospheric pressure is an increase in sublimation rate at higher elevations, if ambient temperature and humidity are the same.

7. Turbulence

Atmospheric turbulence levels, under conditions of interest here, are about 10 percent for streamwise velocity fluctuations, using approximations suggested by Lumley and Panofsky (1964). (The turbulence level is the ratio of root-mean-square fluctuating velocity to free stream velocity.) Measurements summarized by [6] are for turbulence levels of 1 to 3 percent, as noted before. The question is whether the higher natural turbulence level would cause a greater particle sublimation rate by providing more ventilation than predicted by [6].

If a snow particle followed all turbulent accelerations of air motion exactly during windblown transport, then the relative velocity would just equal the particle fall velocity due to gravitational acceleration. However, the particle to air density ratio is close to 1000, assuming the windblown snow particle has a density

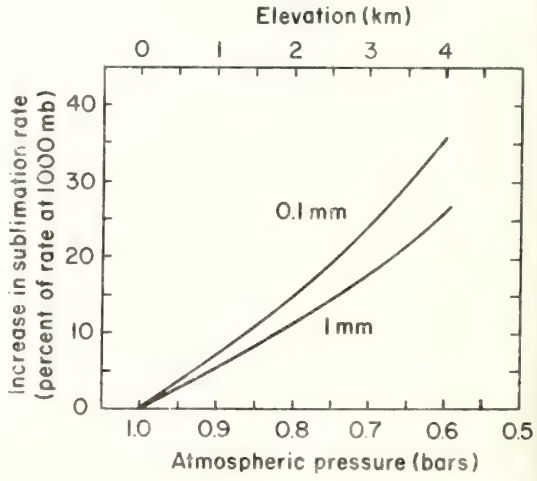
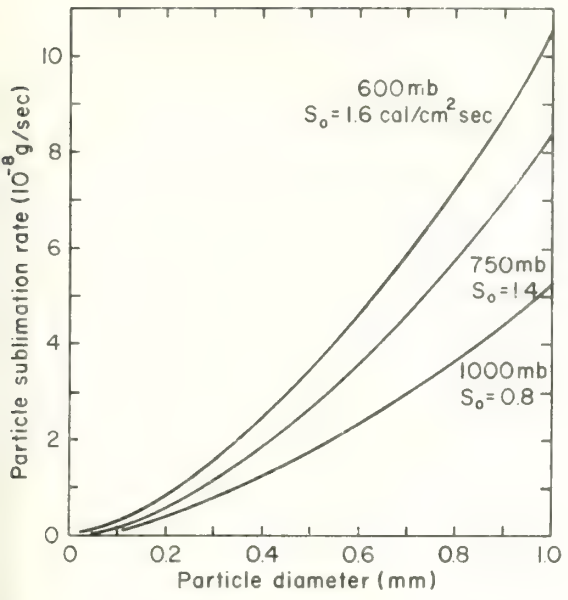


Figure 5.--The sublimation rate for an ice sphere is more rapid at higher elevations according to equation [5] evaluated for -20 C. ambient temperature and a water vapor density equal to 90 percent of the saturation value over ice. A 100 cm/sec ventilation rate was assumed for both particle diameters.



igure 6.--When the increase of solar radiation at higher elevations is included, equations [8] and [9] provide this picture of particle sublimation rates. Ambient conditions again were -20° C. and 90 percent of water vapor density at saturation over ice, with a ventilation rate of 100 cm/sec for all particles.

ear 0.9 g/cm^3 (ice). Accelerations required o overcome particle inertia, and cause it to ollow the air velocity fluctuations, must be reated by additional drag forces. These can nly occur if the relative velocity between the article and air increases. Thus, the instananeous relative velocity, u_R (defined by $_R \equiv u_p - u$, the difference between particle nd air velocities) is a fluctuating vector in urbulent flow. It becomes equal to the parcle fall velocity ($u_p = w$) when the air is alm ($u = o$).

Friedlander (1957) showed that the mean quare relative velocity characterized convection ffects on heat and mass transfer from particles uspended in turbulent flow. By making some ather restrictive assumptions, Tchen (1947) deived equations of motion from a balance of orces on the suspended particle. Hinze (1959) nd Soo (1967) have both summarized his work. A generalized solution to these equations of notion (Chao 1964) gives the mean square elative velocity in terms of the mean square luid velocity, the turbulent energy spectrum, nd a quantity determined from the stochastic quation of relative motion. This relation redicts that particles of a given size will have n energy spectrum that coincides with the nergy spectrum of fluid motion up to some frequency, above which "slip," or relative motion, increases with increasing frequency of turbulent fluctuations.

With the energy spectrum suggested by Lumley and Panofsky (1964) for horizontal gustiness in the atmosphere, Chao's procedure indicates that a 100 μ snow particle would completely follow all turbulent fluctuations. A 1 mm particle would exhibit "slip," that is, it would not follow wind fluctuations, for frequencies higher than 1/10 cycle per second. Csanady (1963) derived a similar equation for mean square relative velocity, by which he calculated that a 0.5 mm dust particle would follow all atmospheric eddies with a vertical dimension greater than 10 m.

The above calculations are based on some rather tentative assumptions, including the absence of particle interactions and particle spin created by the shear flow. More restrictive, drag forces are assumed to obey Stokes' Law, which, strictly speaking, would limit application to situations where the particle Reynolds number is unity or less. An opportunity and need for well designed experiments under atmospheric conditions surely exists here.

Turbulence tends to increase sublimation by increasing the relative velocity above the particle fall velocity. However, the calculations described above do not indicate that this increase is large for the normal size range of windblown snow particles.

B. A Nonspherical Particle

The fine, delicate structures called snowflakes, created during precipitation, are certainly not well approximated by a sphere. As noted in the introduction, these beautiful forms are quickly destroyed by mechanical forces, when wind begins to move deposited snow. This action reduces both the fine structure and the maximum dimensions of the particles, so that the spherical approximation becomes somewhat more realistic. The photomicrographs presented by Budd et al. (1966) and Kojima (1969) all show windblown snow particles without any of the fine dendritic snowflake structure. However, the particles have irregular surfaces and shapes and are more often oblong that spherical.

By the analogy between water vapor diffusion and electrostatics, it is relatively easy to estimate how sublimation rate is affected by deviations from the spherical toward more oblong particle shapes. The calculations in this section show that these deviations tend to increase sublimation rates, but the effect is not large.

1. Diffusion Shape Factor

According to McDonald (1963), the first treatment of the analogy between diffusion and electrostatic fields should be attributed to Maxwell, while Houghton was first to use the analogy in investigating ice-crystal growth. Equation [1], which was derived from this analogy, can be modified to account for particle shape by replacing the radius r with C, the electrostatic capacitance of a conductor with identical size and shape. Then [1] becomes $dm/dt = 4\pi CD(\rho - \rho_r)$. McDonald has verified this analogy for several shapes which also have a theoretical solution in terms of electrostatics, and he measured the value of C for a number of crystal shapes which do not have theoretical solutions.

The four cases in which C may be determined theoretically are (McDonald 1963):

(a) sphere, radius r, $C = r$
(b) thin circular disk, radius r, $C = 2r/\pi$
(c) prolate spheroid, major and minor semi-axis b and c, $C = A/\ln[(b + A)c]$ where $A = (b^2 - c^2)^{1/2}$.
(d) oblate spheroid of major and minor semi-axis b and c. $C = Ae/\sin^{-1}e$ where $e = (1 - c^2/b^2)^{1/2}$.

The limiting value for a thin prolate spheroid, $C = b/\ln(2\,b/c)$ was found to adequately represent the needle crystal form where b is half the needle length and c is the radius of the midsection. McDonald's conclusion was that errors from approximating the true value of C by theoretical values are less than many of the other uncertainties in predicting crystal growth or sublimation.

The sphere has the smallest surface area per unit mass. Any deviation from the spherical shape will increase the area-to-mass ratio, and will result in a larger sublimation rate for a given particle mass. In figure 7, values of C/r are plotted as a function of the ratio of major to minor semi-axis, ξ for a prolate spheroid (formed by revolution of an ellipse about its major axis). For a particle with the same mass as a sphere of radius r, the rate of mass transfer by diffusion would increase 25 percent when the ratio of major to minor semi-axis is 5.

2. Sublimation Equation

When we consider the additional factor of particle shape, equation [8] may be modified to provide a more realistic model. Similar to [3], we have

$$dm/dt = 4\pi DCF_m (\rho - \rho_r) \qquad [10]$$

and in place of [7],

$$L_s \frac{dm}{dt} = 4\pi KCF_h (T_r - T) + Q \qquad [11]$$

where F_m and F_h are the ventilation factors comparable to 1/2 (Sh) and 1/2 (Nu), respectively, and the radius has been replaced by C, the shape factor. Again as outlined by Thorpe and Mason (1966), the Clausius-Clapeyron equation is used to approximate the vapor density difference, and temperature differences are assumed small. The result analogous to [8] is

$$\frac{dm}{dt} = \frac{4\pi C(\rho/\rho_{sT} - 1) - (Q/KT)\left(\frac{L_s M}{RT} - 1\right)\frac{1}{F_h}}{\frac{L_s}{KT}\left(\frac{1}{F_h}\right)\left(\frac{L_s M}{RT} - 1\right) + \frac{1}{D\rho_{sT} F_m}} \qquad [12]$$

Ventilation factors, F_h and F_m, must be evaluated by experiment for a particular particle shape C. From the work of Thorpe and Mason these factors are expected to have the form

$$\left.\begin{aligned} F_h &= A + B\,(Pr)^{1/3}(Re)^{1/2} \\ F_m &= A + B\,(Sc)^{1/3}(Re)^{1/2} \end{aligned}\right\} \qquad [13]$$

where A and B are constants.

The radiation term, Q cannot be used in the form given in [9], but must take into account the projected area corresponding to the particle shape. Thus Q takes the form

$$Q = (1 - \zeta)\,A_1 S_o + (1 - \zeta)\lambda A_2 S_o \qquad [14]$$

where A_1 and A_2 are the projected areas of the particle perpendicular to the direct and reflected solar radiation, respectively. Values for A_1 and A_2 depend on the average particle orientation with respect to the horizontal, and on the sun angle.

3. Comparison with a Spherical Particle

Sublimation rates predicted by [8] for the spherical particle and by [12] for the nonspheric particle cannot be compared exactly, because values for the wind factors F_h and F_m are in general, not known for nonspherical particles. However, at least some idea of the uncertainty can be gained by considering the extreme case of an infinite circular cylinder. Work in hot-wire anemometry (Hinze 1959) has established that, for a circular cylinder with major axis at right angles to the flow

$$(Nu) = 0.42(Pr)^{1/5} + 0.57(Pr)^{1/3}(Re)^{1/2}$$

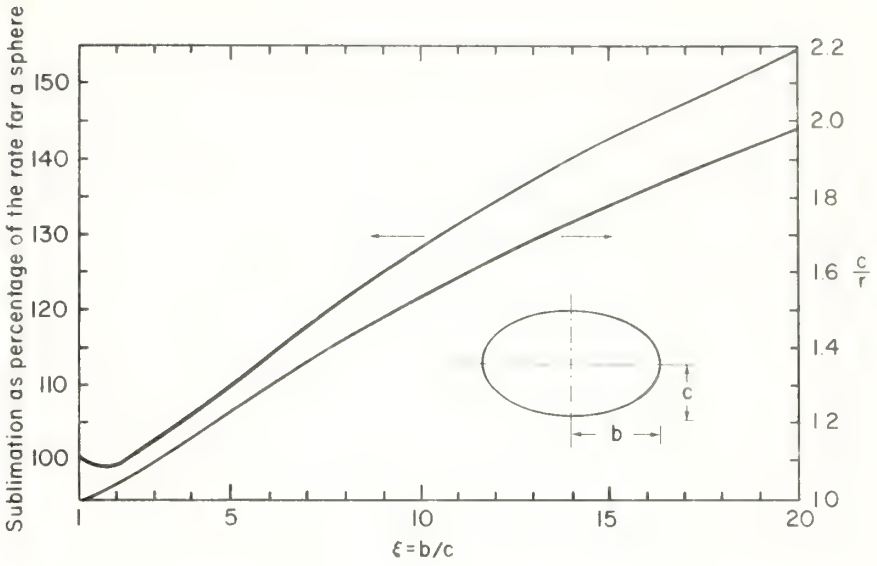


Figure 7.--The sublimation rate of a prolate spheroid of ice, computed from equation [12], is plotted here as a percentage of the rate for a sphere of equal mass. The variation of C/r (the mass diffusion shape factor) is also shown.

At temperatures and pressures examined here, the values of (Pr) are near unity, so that the relation for an infinite cylinder is approximately

$$(Nu) \approx 0.42 + 0.57(Re)^{1/3}$$

compared to the value from [6] for the spherical case ($\xi = 1$)

$$(Nu) = 1.88 + 0.58(Re)^{1/2}$$

Assuming the oblate spheroid approximates an infinite circular cylinder when the ratio of major to minor axis is $\xi = 10^3$, the value of C/r is 13.2 from the limiting approximation C=b/ln(2b/c). Then if the value of (Nu) varies as C/r, for a ratio of $\xi = 20$, the Nusselt number would be $(Nu) \approx 1.76 + 0.58(Re)^{1/2}$, only slightly less than the spherical case. The value of Reynolds number (Re) is taken as $2cV/\nu$, defined by the minor axis of the spheroid (for the long axis perpendicular to the flow). From these approximations, it appears that particle shape has very little effect on the ventilation factor.

Again taking the standard conditions for these calculations (T = -20° C., p = 1000 mb, RH) = 90 percent) with a steady mean ventilation rate of 100 cm/sec, evaluation of [12] with Q = 0 provides the comparison in figure 7. For a ratio of major to minor axis of 5, the sublimation rate without radiation is only about 10 percent larger for the spheroid than for a sphere of the same mass. When radiation is added, $(Q \neq 0)$, the effect of particle shape on sublimation rate depends on the particle's orientation with respect to the sun. The maximum projected area of a prolate spheroid increases as the cube root of eccentricity, so a spheroid with $\xi = 5$, oriented with its long axis perpendicular to the sun's rays, intercepts 1.71 times the radiation intercepted by a sphere of the same volume. A spheroid with the volume of a 100 μ sphere, and with $\xi = 5$, would have almost twice the sublimation rate of the sphere, when oriented so that the shape effects were maximum. However, if the particle orientation during turbulent suspension is random, which seems most likely, the shape effect on radiation interception should disappear.

C. Summary

The objective of Part I was to explore the relative importance of numerous factors that determine the sublimation rate of a single particle. Some conclusions drawn from the various references and calculations are:

1. Ice bulb temperature is a reasonable assumption for the temperature of a sublimating snow particle, so differences in particle and air temperatures will be small (less than 0.5° C.) under natural conditions of blowing snow.
2. The sublimation rate nearly doubles for each 10° C. rise in ambient temperature in the range between -20° C. and 0° C.
3. Particle sublimation more than doubles when the diameter is doubled. The percentage of particle mass lost, however, is greater for smaller sizes.
4. Sublimation of a single particle is directly proportional to undersaturation of the environment with respect to water vapor, when radiation is neglected.

5. Heat transfer by solar radiation can double the particle sublimation rate computed for transfer by conduction and convection alone.

6. The increase in estimated sublimation rate at higher elevations is large enough to be important. For the same temperature, humidity, and ventilation velocity, the rate at 4 km (13,000 feet) is about 30 percent more than that computed for sea level, neglecting radiation. When solar radiation and its increase with elevation are considered, the rate computed for 4 km is approximately 50 percent higher than at sea level.

7. Atmospheric turbulence should cause sublimation rates higher than those predicted from laboratory studies, but tentative calculations indicate this effect is not large, for snow particles less than 1 mm in diameter. Field measurements are certainly needed to test this conclusion.

8. Particle shape appears to have less effect on sublimation than most of the factors considered. The calculated rate for a spheroid with a ratio of major to minor axis as large as 5, is only 10 percent greater than for a sphere.

If a spherical ice particle, ventilated at 100 cm/sec, starts sublimating in an environment with 90 percent relative humidity at 1000 mb pressure (sea level) and -20° C., without any radiation transfer, then increases in radiation, elevation, turbulence, and eccentricity all tend to increase the sublimation rate. Even if all these factors are neglected, an ice sphere 100 μ in diameter, under the conditions above, has a computed loss of mass equal to approximately 19 percent of its total weight in 1 minute. This calculation indicates that the sublimation of blowing snow is important enough to explore further.

PART II
SUBLIMATION FROM A VOLUME OF AIR AND SNOW

Having considered the sublimation of a single particle, and the importance of factors that govern this rate, the next question is, how do the results of Part I apply to sublimation rates from many snow particles in a volume of air? The two major problems discussed in this part of the argument are (1) effects of particle concentration on transfer of heat, mass, and momentum within the volume; and (2), sublimation rates for a distribution of particle sizes. The results show that even maximum natural concentrations are low enough that particle interactions can be ignored, and particle sublimation estimates derived in Part I apply directly to each particle within the volume of air and snow.

A. Concentration Effects on Particle Sublimation

The expressions in Part I, for sublimation of a single particle, were based on assumptions that humidity and temperature gradients extended to infinity. Additional particles in a unit volume present sources of water vapor closer to the particle in question, and may thus reduce the rate of mass transfer. As concentration increases, the drag force experienced by the particles increases, once the interparticle spacing becomes small enough that the fluid boundary layers around the spheres interact. Surrounding particles represent heat sinks that reduce the temperature gradients around a given particle, and radiation scattered by other particles also modifies the heat transferred to the particle in question. The importance of these effects on sublimation rate depends on the concentration of particles.

1. Maximum Natural Concentrations

Estimates of the concentration of snow in air during transport are available from the experiments of Budd et al. (1966) in Antarctica. If the lowest centimeter of snow drift is neglected, concentrations approach the mass density of air, and since this argument is limited to evaporation of particles in suspended transport, the maximum concentration of snow will be taken as $M \simeq \rho_a$. (Below 1 cm, transport is mainly by saltation and creep.) The volume fraction of particles is the ratio of volume occupied by solids to the total unit volume, denoted by ϕ. This ratio, multiplied by particle density (ρ_p), gives the mass con-

entration of snow, $M = \rho_p \phi$. For maximum onditions, where the mass of snow is equal o the mass of air in a unit volume, $\phi = \rho_a/(\rho_a+\rho_p)$. With $\rho_a = 1 \cdot 10^{-3}$ g/cm^3 and $\rho_p = 0.9$ g/cm^3, $\simeq \rho_a/\rho_p$, so only about one thousandth f a unit volume is occupied by snow at maxiium concentrations above the one centimeter evel.

. Correlations of Concentration and Transfer Processes

Studies which correlate mass transfer with oidage $(1 - \phi)$ show that even the maximum oncentration of snow expected above 1 centiieter would cause no important reduction in ass transfer due to particle interaction. These easurements were made by Chu et al. (1953), ullin and Treleaven (1962), and are sumarized by Soo (1967). Marshal and Langleben 1954) expressed the effect of a cloud of water rops on the growth of an ice crystal by a erm equal to the sum of all drop radii in a urrounding unit volume. This approach also eads to the conclusion that the concentrations resent during snow transport by wind do not ignificantly reduce mass transfer from that f an isolated sphere.

The correlation of drag coefficient with eynolds number, at the voidage level coresponding to maximum snow concentration, ndicates no measurable increase in drag at eynolds numbers less than 200 (Soo 1967, ig. 5.2). If drag, and thus relative velocity, re not altered, then convection effects on parcle sublimation are independent of snow conentration under natural conditions.

No studies that correlated voidage with onduction and convention of heat were found. owever, no important changes in these modes f heat transfer are expected, even at maximum oncentrations of snow in turbulent suspension. his inference depends on the close analogy etween mechanisms of heat and mass transfer luring particle sublimation. The nearly identical alues of Nusselt and Sherwood numbers, noted n [6], strongly support the conclusion.

Heat transfer by radiation is a completely ifferent process, and the argument reaches no lear conclusion in this case. If each snow article in a volume of air receives only radiion from outside the volume, and none of the adiation scattered by surrounding particles, the rocess is called "single scattering," and heat ransfer by radiation is independent of particle oncentration. Multiple scattering occurs within he volume when the particles interact. Based n remarks by van de Hulst (1957), single cattering probably applies over most of the natural snow concentration range, and can certainly be made to apply in calculations by limiting the dimensions of the volume considered.

In summary, concentrations of natural windblown snow particles are small enough that particle interactions can be ignored for estimates of the rate at which snow sublimates in a volume of air. Thus, within the limits of optical path length to which single scattering applies, the sublimation rate for a volume is simply the sum of individual particle rates. If the mass of snow per unit volume (M) is composed of N uniform spheres, each with mass, m, sublimating at a rate, dm/dt, then a good approximation of the total sublimation from particles in the unit volume would be $Ndm/dt = (M/m)dm/dt$.

B. Effect of Nonuniform Particle Sizes

Size distributions of windblown snow particles measured by Kojima (1969), Budd et al. (1966), and Lister (1960), show that sizes range from a few microns up to 300 μ or more. The more recent studies also show skewness of the size distributions toward smaller particles. Because the sublimation rate depends strongly on particle size, it is important to take the distribution of sizes into account in this model.

1. General Relationships for Nonuniform Sizes

Suppose a unit volume of air-snow mixture contains N snow particles which have a total mass M. A nominal particle diameter, x, may be defined so that the particle mass is given by $m = \rho_p(\pi x^3/6)$. Let some function $f(x)$ describe the frequency distribution of nominal diameters in the unit volume. Then the number of particles with nominal diameters in the range x to $(x + dx)$ is $Nf(x)dx$, the total number of particles times the relative frequency for that increment of the particle size distribution. Multiplying the mass of a particle with diameter x and the number of particles in this size increment gives the mass of all particles with diameters from x to $(x + dx)$

$$M_x = (\rho_p \pi x^3/6) N f(x) dx \qquad [15]$$

Integrating [15] with respect to particle size, and rearranging terms, the total number of snow particles in the unit volume is

$$N = M/[(\rho_p \pi/6) \int_0^\infty f(x) x^3 dx] \qquad [16]$$

This relation determines the number of particles in a unit volume of air and snow when the mass concentration and particle size distribution are known.

Let $(dm/dt)_x$ denote the sublimation rate for a particle with nominal diameter in the range from x to (x + dx). Then the rate of sublimation, $(dM/dt)_x$ for the mass associated with this particle size increment, is equal to the number of particles of this size, multiplied by the single particle sublimation rate,

$$(dM/dt)_x = (dm/dt)_x N f(x)dx \qquad [17]$$

Summing rates from all particle size increments gives the sublimation rate for the unit volume, so that by integrating [17] with respect to particle diameter,

$$(dM/dt) = N\int_0^\infty (dm/dt)_x f(x)dx \qquad [18]$$

This is a general expression for the rate at which a mass of nonuniform particles sublimates in a unit volume of air and snow. The functional form of $(dm/dt)_x$ was discussed in Part I. Possible forms for the distribution function, $f(x)$ are considered below.

2. Specific Size Distributions

Studies that report size distributions for drifting snow are too few to assure a general distribution function. Several reasonable forms are discussed here, and evaluation of [18] with the two-parameter gamma function suggested by Budd (1966) provides an example.

An exponential function that depends on precipitation rate and crystal type describes the size distributions of aggregate snowflakes during precipitation, according to measurements by Gunn and Marshall (1958) and Ohtake (1970). Within a few hours after snowfall, the number of windblown snow particles in a size class decreases exponentially with increasing size.[4] This work shows that, after several hours of snow drifting without precipitation, a logarithmic-normal function provides a better description of the drift particle size distributions.

Budd (1966) shows that the log-normal function gives a fair approximation to the size distributions reported in Budd et al. (1966). For his calculations of drift content, however Budd used a two-parameter gamma functio which gave as good a fit to the size distribu tions, and was mathematically more convenien for his purpose. Following his suggestion, th distribution of particle size is specified as

$$f(x)dx = \frac{1}{\beta^\alpha \Gamma(\alpha)} e^{-x/\beta} x^{\alpha-1} dx \qquad [19]$$

where α and β are the parameters of the dis tribution, such that $\alpha\beta$ is equal to the mean and $\Gamma(\alpha)$ is the complete gamma function The shape parameter is α, and β is the scal parameter (Thom 1958).

With a specified particle size distribution [16] will yield an expression for the numbe of nonuniform particles in a unit volume. Sub stituting the expression [19] for $f(x)$ in [16 gives the number of particles in terms of mas concentration and particle size:

$$N = M/\left[(\rho_p \pi/6)\int_0^\infty \frac{1}{\beta^\alpha \Gamma(\alpha)} e^{-x/\beta} x^{(\alpha+3)-1} dx\right] [20$$

By the definition of a gamma variate and th fact that the area under a distribution functio must equal unity, [20] can be solved to giv the number of particles per unit volume i terms of the mass concentration of snow an the parameters of the size distribution,

$$N = M(6/\rho_p \pi)[\Gamma(\alpha)/\Gamma(\alpha + 3)]\beta^{-3} \qquad [2$$

The sublimation rate of this particular distribu tion of particles is determined from [18]. Th integration cannot be performed, however, unt a relationship between particle size and vent lation rate is formulated.

3. Particle Size and Ventilation Velocity

A ventilation rate equal to the particle fa velocity was assumed in Part I, when t effects of turbulent air accelerations we neglected. Continuing with this tentative a sumption, a deterministic relationship betwe particle size and fall velocity will admit int gration of [18].

Mellor (1965) summarizes the problem expressing the fall velocities of drifting sno in terms of particle size. For diameters le than 60 μ, particles obey Stokes' Law reaso ably well, and fall velocity is proportional the second power of diameter. In the ran between 100 μ and 1 mm, fall velocity is direc proportional to the first power of diamet Although drifting snow particles larger th

[4] *Schmidt, R. A. Distributions of snow particle size during wind transport over a ridge. (Manuscript in preparation at Rocky Mt. Forest and Range Exp. Stn., Fort Collins, Colo.)*

1.5 mm usually are not transported by turbulent suspension, such particles fall at speeds proportional to the square root of diameter. Recognizing that transitions must occur between these ranges, Mellor suggested the relation, $w = w_o \exp(-x_o/x)$, for fall velocities of drift particles less than about 5 mm diameter. In this expression, w_o is the terminal velocity of large particles with x_o diameter.

In his analysis, Budd (1966) assumed the fall velocity of all suspended drift particles was $w = C_2 x$, noting that this relationship would be in error for the small particles. Depending on particle shape, the proportionality constant C_2 was between 2440/sec and 3880/sec, the latter applying to spherical particles. This assumption is used in the following calculation, which does not warrant the more complicated relation suggested by Mellor.

. Calculation of Volume Sublimation Rate

To estimate a sublimation rate by [18], first the total mass of snow in the volume of air is required. With this value for M, and a size distribution function, such as [19], the number of particles in the volume can be calculated from [16]. Finally, an expression for single-particle sublimation, such as [12] derived in Part I, is combined with some relation between particle size and ventilation velocity to give an integrable expression for $(dm/dt)_x$ in [18].

As an example, suppose the volume of interest is a horizontal layer of snow and air, 1 cm thick and 1 m square. (The reason for considering these dimensions becomes apparent in Part III.) If this layer is located 1 m above a horizontal snow surface, then a snow concentration of 1 g/m^3 might be expected for 15 m/sec wind velocities, according to Antarctic measurements by Budd et al. (1966). The mass of snow (M) in the given volume would be 0.01 g.

If the distribution of sizes is approximated by [19], then parameters α and β must be specified. Budd (1966) obtained values of the shape parameter (α) near 15. Calculations here are for several mean diameters($\bar{x} = \alpha\beta$), with $\alpha = 15$, so that only the scale parameter (β) varies. These distributions are plotted in figure 8.

Nighttime, or minimum radiation transfer ($Q = 0$) is assumed, and particle shape effects are neglected so that equation [5] is used in place of [12] to express single particle sublimation. If [5] and [6] are combined, the expression is

$$\frac{dm}{dt} = C_1[1.88x + 0.58x\,(Vx/\nu)^{1/2}] \qquad [22]$$

where the mathematical presentation is considerably reduced by the substitution

$$C_1 = \frac{\tau}{\frac{L_s}{KT}\left[\frac{L_s M}{KT} - 1\right] + \frac{1}{D\rho_s(T)}} \qquad [23]$$

Assuming that ventilation velocity is equal to particle fall velocity ($V = w$), and further, that fall velocity is directly proportional to particle diameter ($w = C_2 x$), the rate of sublimation for a spherical particle is

$$(dm/dt)_x = C_1[1.88x + 0.58\,(C_2/\nu)^{1/2}x^{3/2}] \qquad [24]$$

For all particles in the unit volume, the sublimation rate is estimated by

$$(dM/dt) = [NC_1/\beta^{\alpha}\Gamma(\alpha)]\int_o^{\infty}[1.88\,x + 0.58 \qquad [25]$$

$$(C_2/\nu)^{1/2}\,x^{3/2}]e^{-x/\beta}\,x^{\alpha-1}dx$$

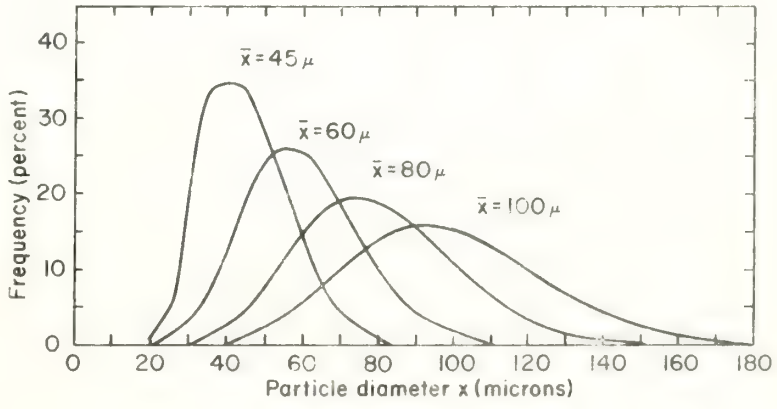


Figure 8.--These particle size distributions are used for the calculations in table 1 and figure 9. The two-parameter gamma function has a mean $\bar{x} = \alpha\beta$. The value $\alpha = 15$ was taken for all distributions.

where N is computed from [21] and C_1, defined by [23], is constant for a given set of temperature, pressure, and humidity conditions.

The results of evaluating [25] for the several size distributions, sublimating at -20° C., 1000 mb and 90 percent relative humidity, are shown in figure 9. A value of $C_2 = 3880$/sec was used for spheres, and particle density was assumed equal to 0.92 g/cm^3. Sublimation rate increases markedly when the same mass of snow is composed of particles with smaller and smaller mean diameters. Skewness of size distributions toward smaller diameters has the same effect of increasing surface area and thus sublimation.

An average particle sublimation rate may be computed by dividing the total number of particles into the volume sublimation rate. Equating this value and the righthand side of [24] gives the diameter of a particle with the average sublimation rate. These calculations were carried out for the four distributions in figure 8 (table 1). Average sublimation diameters are nearly the same as the distribution mean diameters for these examples.

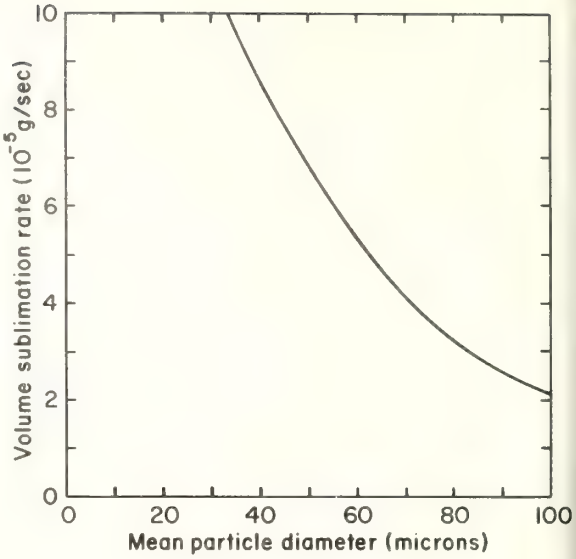


Figure 9.--The sublimation of a given mass of snow greatly increases as the mean particle diameter decreases according to this plot. Equation [25] was evaluated with the size distributions in figure 8 to estimate the sublimation rate of 0.01 gram of snow in a 10^4 cubic centimeter volume at -20° C. and 1000 mb. Water vapor density was again 90 percent of saturation over ice.

C. Summary

Concerning the effect of snow concentration on transfer processes, the following conclusion was drawn:

1. For heights greater than 1 cm above the snow surface, natural windblown snow concentrations are too low to have an effect on heat, mass, and momentum transfer, so that the relations developed for a single sphere in Part I apply to each particle in a volume of drifting snow. It follows that the total sublimation of snow in a volume is the sum of the sublimation rates for each particle as if it were isolated.

Introduction of a particle size distribution produced calculations summarized by figure 9 which led to the conclusion that:

2. Sublimation of a mass of snow in a volume of air is extremely sensitive to the distribution of particle sizes, due to the surface area relationship. However, there is apparently little error in computing sublimation for N spheres with the same diameter as the mean of the distribution, at least for the distribution function and sizes considered.

Table 1.--Comparison of average sublimation diameters, $\bar{x}_s$

Mean diameter ($\bar{x}$ in)	Total number N	Volume sublimation rate (dM/dt) in g/sec	Average particle rate (dM/dt)/N in g/sec	Average sublimation diameter ($\bar{x}_s$ in μ)
100	17,220	$2.19 \cdot 10^{-5}$	$1.272 \cdot 10^{-9}$	102
80	33,690	$3.17 \cdot 10^{-5}$	$9.409 \cdot 10^{-10}$	81
60	79,850	$5.18 \cdot 10^{-5}$	$6.487 \cdot 10^{-10}$	61
40	189,300	$8.59 \cdot 10^{-5}$	$4.538 \cdot 10^{-10}$	45

PART III
SUBLIMATION IN A VERTICAL COLUMN OF DRIFTING SNOW

Natural concentrations of drifting snow decrease very rapidly with height, and average particle size also becomes smaller in the first few meters above a snow surface. When these changes are expressed as a function of the mean wind velocity profile, the volume sublimation rate (Part II) can be integrated with height, to predict the sublimation rate in a vertical column of drifting snow. Evaluation of this general, steady-state equation indicates that water losses through the sublimation process are potentially quite important in a water balance. The vertical fluxes of heat and water vapor required to maintain a steady state provide an interesting set of conditions for the vertical profiles of temperature and humidity.

A. General Equation for Steady-State Sublimation

When snow is drifting, speeds are high enough that the vertical profiles of wind in the first 10 meters above a horizontal surface are very well expressed by

$$\bar{u} = (u_*/k)\ \ln(z/z_o) \qquad [26]$$

according to the Antarctic measurements. The mean horizontal wind component ($\bar{u}$) is proportional to the natural logarithm of height (z) measured vertically from the surface. A friction velocity ($u_* \equiv \sqrt{\tau_o/\rho_a}$), defined by the ratio of surface shear stress to air density, and von Karman's constant ($k = 0.4$) determine the proportionality factor. The integration constant (z_o) is often called a "roughness parameter" because its value depends on conditions of the horizontal surface.

For this windspeed profile relation, the eddy viscosity is $\varepsilon = ku_*z$. Shiotani and Arai (1953), and Loewe (1956), assumed the eddy diffusivity of uniform snow particles was equal to the eddy viscosity. Then, equating the vertical flux of snow by turbulent exchange with the downward flux due to gravity provides an expression for the relative number of particles at any height, in the form

$$N_z/N_Z = (z/Z)^{-w/ku_*} \qquad [27]$$

The number of particles (N_Z) at some reference height (Z) must be known to evaluate N_z from [27]. This equation also holds for the mass concentration ratio as long as all particles have the same mass. (Sommerfeld and Businger (1966) presented measurements which cast some doubt on the assumption that particle diffusivity and eddy viscosity are equal. However, as Radok (1968) points out, their measured particle fall velocities seem unreasonably high, which could account for the discrepancy. If particle "slip" is negligible, the assumption should be valid, and the argument will continue with caution.)

Budd (1966) assumed that particles in each small size class were distributed with height according to [27]. Photoelectric particle counter measurements[5] support this assumption. When N_{zx} denotes the number of particles at some height z, in a nominal diameter class x to $(x + dx)$, this assumption is formalized by

$$N_{zx} = N_{Zx}\,(z/Z)^{-w/ku_*} \qquad [28]$$

Then if $f(x)$ is the distribution function of nominal diameters in a unit volume at the reference height (Z), the number of particles in a size class at that height is $N_{Zx} = N_Z f(x)dx$, and thus

$$N_{zx} = N_Z(z/Z)^{-w/ku_*} f(x)\ dx \qquad [29]$$

For all particles at height z, with nominal diameters between x and $(x + dx)$, the sublimation rate is $(dM/dt)_{zx} = N_{zx}\,(dm/dt)_x$, or

$$(dM/dt)_{zx} = N_Z(dm/dt)_x(z/Z)^{-w/ku_*}f(x)\ dx \qquad [30]$$

Integrating this expression with respect to nominal diameter (x) gives a relationship for volume sublimation rate at height z as

$$(dM/dt)_z = N_Z \int_o^\infty (dm/dt)_x(z/Z)^{-w/ku_*} f(x)dx \qquad [31]$$

The final step toward a general steady state expression for sublimation within a vertical column of drifting snow is to apply [31] to a small volume with vertical increment dz, and integrate with height, to get $(dM/dt)_c$, the total rate for the column as

$$(dM/dt)_c = N_Z \int_o^Z \int_o^\infty (dm/dt)_x\,(z/Z)^{-w/ku_*} f(x)dxdz \qquad [32]$$

[5] *Schmidt, R. A. Distributions of snow particle size during wind transport over a ridge. (Manuscript in preparation at Rocky Mt. Forest and Range Exp. Stn., Fort Collins, Colo.)*

Evaluation of this expression requires the following:

a. the mass or number concentration at the reference height, to provide N_Z ;
b. a functional expression for the size distribution, $f(x)$;
c. at least two points on the wind profile, to determine the friction velocity, u_*;
d. some expression for particle fall velocity (w) in terms of the nominal particle diameter (x);
e. an integrable relation for the single particle sublimation rate.

B. Calculations for Constant Temperature and Humidity

The objective of evaluating [32] at this point is to demonstrate the potential magnitude of drift snow sublimation, even under relatively cold, moist conditions. Calculations are for a vertical column, 1 meter square in horizontal cross section and extending from 1 cm to 10 m above the horizontal snow surface. Average windspeed at 10 m is 15 m/sec, friction velocity (u_*) is 52 cm/sec, and Z = 1 m is specified for a reference height. As in Part II, the mass of snow in a 1 cm layer at this level is assumed to be 0.01 g, with particle sizes distributed as a two-parameter gamma function where $\alpha = 15$, and $\bar{x} = 100\ \mu$. The number of particles (N_Z) in this layer has been calculated as 17,220.

Since sublimation depends strongly on particle surface area, and therefore particle concentration, the vertical drift concentration profile is an important part of sublimation calculations for a column. A general equation for the mass of snow in a layer at any height z may be derived from [29] as

$$M_z = N_Z\ (\pi\rho_p/6) \int_0^\infty (z/Z)^{-w/ku_*x^3} f(x)\ dx \qquad [33]$$

When Budd's assumptions for fall velocity ($w = C_2 x$) and size distribution [19] are made, the drift concentration profile is given by

$$M_z = M_Z\ (1 - C_2 e/ku_* \ln z/Z)^{-(\alpha+3)} \qquad [34]$$

Figure 10 compares the average of profiles measured by Budd et al. (1966, p. 95), for 14.5 m/sec mean windspeed, with the concentration profile computed by [34]. To obtain a reasonable prediction, the value $C_2 = 2440$/sec had to be used. The value $C_2 = 3880$/sec (for spheres) predicted too rapid a decrease in concentration with height. (One should not conclude too much about particle shape from the comparison, since the assumption $w = C_2 x$ only roughly approximates the true relationship for much of the size range.)

An estimate of the mass transfer shape factor (C in Part I), which corresponds to the value of $C_2 = 2440$/sec, can be derived from drag coefficient - Reynolds number correlations for irregular particle shapes. One such compilation of measurements is presented in Report 12 of the Subcommittee on Sedimentation (Inter-Agency Committee on Water Resources U.S.A. 1958). Comparisons of fall velocities predicted by $w = C_2 x$ with those given by the drag curve for different particle shapes indicate that the capacitance C would be only about 4 percent greater than for a sphere (C = x/2), even when $C_2 = 2440$/sec. The conclusion is: even though particle shape plays an important role in determining the drift concentration profile, no large error in sublimation rate is introduced when single particle rates are computed for the spherical case.

This conclusion leads to the particle sublimation rate equation [8], which, with [6] and the assumption $w = C_2 x$, again result

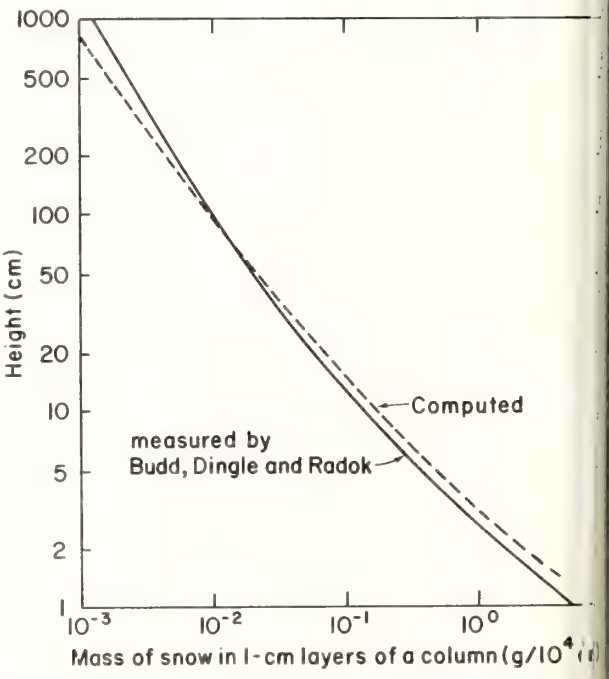


Figure 10.--The snow concentration profile computed from equation [34] with C_2 = 2440/sec compares reasonably with the average drift density profile reported by Budd et al. (1966) for windspeeds near 14.5 m/sec. Values used in the calculations included a 10-m windspeed of 15 m/sec, u_* = 52 cm/sec, α = 15 and $\bar{x}$ = 100 microns. The drift density at the reference level Z = 1 m was assumed to be $M_Z = 0.01\ g/10^4 cm^3$.

n [24] for particle sublimation without radiation (Q = 0). When this expression for $(dm/dt)_x$, and the distribution function [19], are substituted in [31] the sublimation within a layer at height z is

$$\left(\frac{dM}{dt}\right)_z = \frac{N_Z C_1}{\beta^{\alpha}\Gamma(\alpha)} \int_0^{\infty} [1.88x^{\alpha} + 0.58(C_2/\nu)^{1/2} \quad [35]$$

$$x^{\alpha+1}]e^{(C_2 a - 1/\beta)x} dx$$

where the substitution $a = (1 ku_*) \ln z/Z$ has been used with the identity, $(z/Z)^{-C_2 x/ku_*} \equiv \exp(C_2 ax)$. Evaluating the integral gives

$$\left(\frac{dM}{dt}\right)_z = N_Z C_1 \bar{x}(1 - C_2 a\beta)^{-(\alpha+1)}[1.88 + \quad [36]$$

$$0.58(C_2/\nu)^{1/2}(\bar{x}+\beta)/(1-C_2 a\beta)]$$

The final step of integrating [36] with respect to height does not lead to an analytical ex-

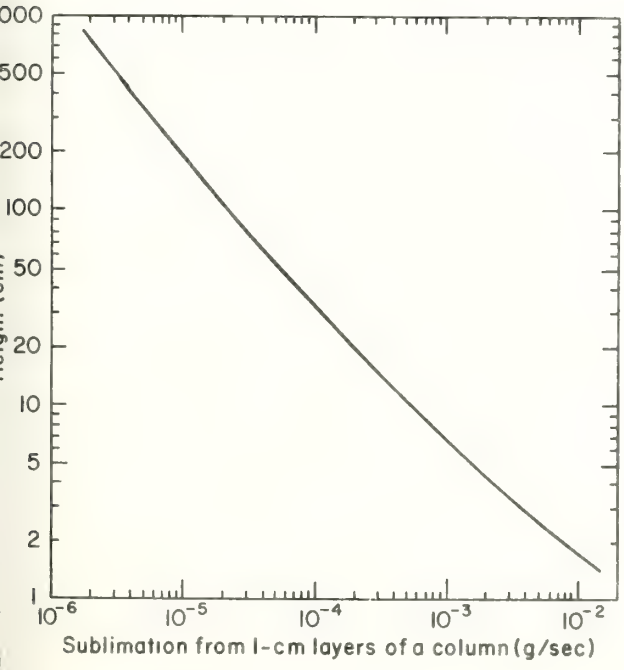


Figure 11.--Assuming the humidity is constant with increasing height (in this case, 90 percent of the saturation value over ice at -20° C.), the sublimation rates in 1-centimeter layers of a column of air and snow show a variation with height similar to the snow concentration profile. Values in this figure were computed by equation [36] for the calculated concentration profile in figure 10.

pression for the total column sublimation. An approximation has therefore been obtained by summing the sublimation rates computed by [36] for each of the layers 1 cm thick and 1 m square that make up the column of drift snow being considered. For this example, the variation of volume sublimation with height is plotted in figure 11, which illustrates the strong influence of the concentration profile. The mass of snow computed from the concentration profile was 14 g for the column, and the estimated sublimation rate $(dM/dt)_c$ was $3.9 \cdot 10^{-2}$ g/sec. Neglecting the strong influence of radiation, even at -20° C. and 90 percent relative humidity, the estimated snow sublimation rate is 0.28 percent each second, which, if conditions were somehow maintained, would be almost 17 percent per minute.

C. Vertical Fluxes under Steady Conditions

To maintain steady humidity and temperature conditions within the column of drifting snow, water vapor must be removed, and heat added, at rates that balance the sublimation process. With no horizontal gradients of vapor or temperature (steady state), turbulent transfer of vapor to the atmosphere above the column requires a vertical humidity gradient. Heat is added to the column from the snow surface by turbulent exchange along a vertical temperature gradient (forced convection), although both direct and reflected solar radiation may also transfer heat to particles in the column. Thus, radiation and the vertical temperature and humidity profiles interact with the sublimation profile to establish an equilibrium in this steady state model.

1. Humidity Profile

If the humidity of some thin horizontal layer in a column of drifting snow remains constant with time, the sublimation rate of that layer must be matched by an increase in the vertical water vapor flux across the layer. Thus

$$\frac{\partial E}{\partial z} = \left(\frac{dM}{dt}\right)_z \quad [37]$$

where E denotes the vertical vapor flux due to turbulent exchange. Following Priestly (1959), the vertical flux of water vapor, E, is written

$$E = -\rho_a K_w (\partial \bar{q}/\partial z) \quad [38]$$

where q is the specific humidity (the mass of water vapor divided by the mass of moist air) and K_w is the eddy diffusivity for water vapor. Similarly, for momentum flux τ and eddy viscosity (K_m) the defining equation is $\tau = \rho_a K_m(\partial\bar{u}/\partial z)$. Specific humidity may be written as $q = \rho/\rho_a$ and when the density of moist air (ρ_a) is considered constant over the column height, the humidity gradient is $(\partial\rho/\partial z)=\rho_a(\partial q/\partial z)$. If one makes the basic assumption that eddy diffusivity is equal to eddy viscosity ($K_w = K_m$), the vertical vapor flux, in terms of the humidity and windspeed gradients, is

$$E = \frac{-\tau}{\rho_a} \frac{\rho_a(\partial\overline{q}/\partial z)}{(\partial\overline{u}/\partial z)} \qquad [39]$$

Recalling that $u_* \equiv \sqrt{\tau/\rho_a}$, the flux may be rewritten

$$E = -u_*^2(\partial\rho/\partial z)/(\partial\overline{u}/\partial z) \qquad [40]$$

where the profile of specific humidity has been written in terms of vapor density or absolute humidity, ρ. From the logarithmic wind profile, the windspeed gradient is $(\partial\bar{u}/\partial z) = u_*/kz$, neglecting the zero displacement z_o. So, for conditions of interest here (near neutral stability), the vertical vapor flux is estimated from

$$E = -u_* kz(\partial\rho/\partial z) \qquad [41]$$

By definition $\sigma \equiv (\rho/\rho_{sT}-1)$, and thus $\partial\rho/\partial z = \rho_{sT}\partial\sigma/\partial z$ so [41] may be written as $E = -(u_* k\rho_{sT})z(\partial\sigma/\partial z)$ and differentiation gives

$$\frac{\partial E}{\partial z} = -(u_* k\rho_{sT})\left(z\frac{\partial^2\sigma}{\partial z^2} + \frac{\partial\sigma}{\partial z}\right) \qquad [42]$$

The equilibrium condition [37] equates [42] with the general expression [31] for $(dM/dt)_z$ to give a differential equation for the humidity profile.

$$\frac{\partial^2\sigma}{\partial z^2} + \frac{1}{z}\frac{\partial\sigma}{\partial z} + \frac{N_Z}{u_* k\rho_{sT} z}\int_o^\infty (dm/dt)_x \qquad [43]$$

$$(z/Z)^{-w/ku_*} f(x)dx = 0$$

Single particle sublimation $(dm/dt)_x$ also contains the variable σ, and for the steady state, this equation is an ordinary differential equation of second order, with variable coefficients. If P, Q, and R denote functions of height, and a prime indicates differentiation with respect to z, [43] has the general form

$$\sigma'' + P\sigma' + Q\sigma = R \qquad [44]$$

where $R = 0$ when radiation is neglected.

Perhaps because of the unfortunate combination of assumptions, no solution for the humidity profile was obtained with the assumption $w = C_2 x$ and the two-parameter gamma distribution for $f(x)$. Nevertheless, a general picture of the humidity profile curvature is gained from the vertical vapor flux equation [41].

If humidity decreases in direct proportion to the logarithm of height (say $\rho = \rho_{sT} - A\ln z$) then the humidity gradient is inversely proportional to height ($\partial\rho/\partial z = -A/z$), and according to [41], the vapor flux is constant with height. However, to exhaust the vapor created by sublimation, E must increase with height to match $\int^z (dM/dt)_z dz$ as shown by figure 12. Therefore, the humidity profile must be such that $z\partial\rho/\partial z$ increases with height, rapidly at first. Such a profile is sketched in figure 13 along with the logarithmic humidity profile. Since the sources of water vapor are distributed with height, the vertical humidity profile in drifting snow might resemble that in a layer of transpiring vegetation.

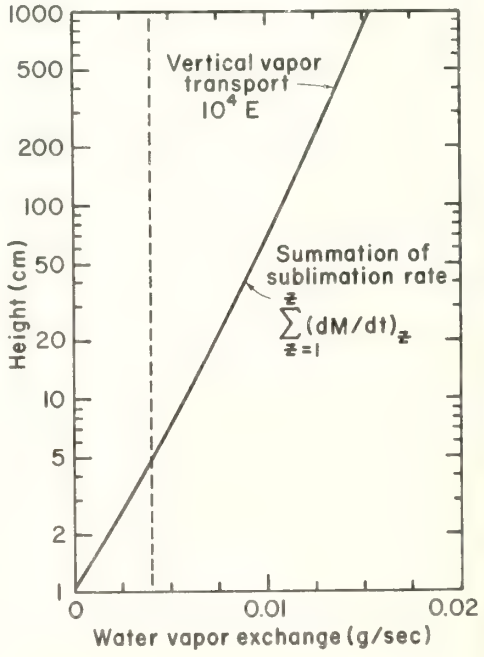
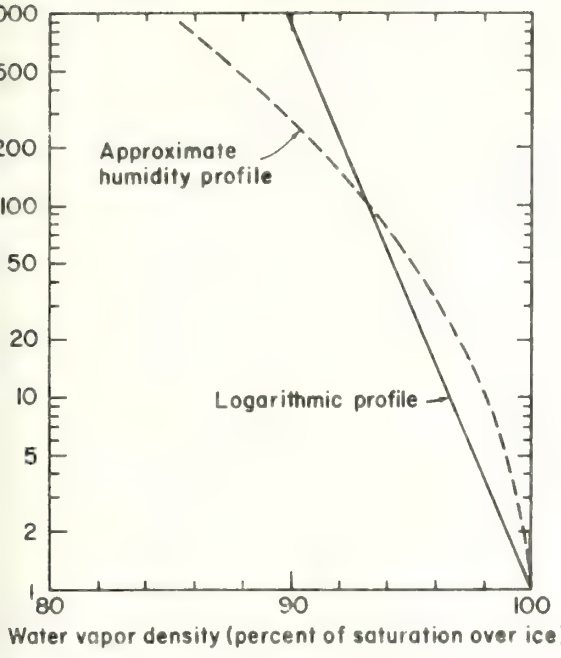


Figure 12.--A logarithmic humidity profile should correspond to constant vertical vapor transport with height. However, the total sublimation increases with height so that such a humidity profile would not indicate the required balance between vertical vapor flux and sublimation rate. The humidity profile used in these calculations was $\sigma_z = \sigma_{100}(1 + 0.217\ln z/Z)$, *where* σ_{100} *is the undersaturation at 100 cm, (taken as 0.1).*



igure 13.--To maintain a balance between steady-state vertical vapor transport and sublimation of blowing snow, the humidity profile is expected to be similar in shape to the one sketched here.

. Temperature Profile

For the vertical heat flux (H), a defining quation analogous to [38], is given by Priestley 1959) as

$$H = -\rho_a C_p K_h \left(\frac{\partial T}{\partial z} + \theta\right) \qquad [45]$$

The turbulent heat-transfer coefficient is K_h, nd the adiabatic lapse rate (θ) is approxiately -0.01° C/m. Then, with the logarithmic ind profile and the assumption that $K_h = K_m$, he equation becomes

$$H = -\rho_a C_p u_* kz \left(\frac{\partial T}{\partial z} + \theta\right) \qquad [46]$$

To maintain a steady sublimation rate within ome layer at height z, the amount of heat equired is $L_s (dM/dt)_z$. If this heat is transerred to the layer entirely by turbulent exhange, the vertical heat flux is reduced by his amount across the layer so that the equiibrium condition is

$$\frac{\partial H}{\partial z} = -L_s (dM/dt)_z \qquad [47]$$

Differentiating [46] provides the steady-state equation for the temperature profile in a form analogous to [43].

$$\frac{\partial^2 T}{\partial z^2} + \frac{1}{z}\left[\frac{\partial T}{\partial z} + \theta\right] + \frac{L_s}{\rho_a C_p u_* k z^2}\left(\frac{dM}{dt}\right)_z = 0 \qquad [48]$$

When direct and reflected solar radiation are included, the decrease in turbulent heat flux with height supplies the difference between heat used in sublimation and that transferred to the layer by radiation (Q_z). Then the equilibrium condition is

$$\partial H/\partial z = -\left[L_s \, dM/dt - Q_z\right] \qquad [49]$$

where the radiation (Q_z) absorbed by particles in the volume at height z is

$$Q_z = N_z S_0 (1 + \alpha) \int_0^\infty (1 - \alpha) \pi/4 \, x^2 \, \tau(x) dx \qquad [50]$$

if single scattering applies throughout the column. The temperature profile may be obtained from the differential equation,

$$\frac{\partial^2 T}{\partial z^2} + \frac{1}{z}\left[\frac{\partial T}{\partial z} + \theta\right] - \frac{L_s}{\rho_a C_p u_* k z}\left(\frac{dM}{dt}\right)_z = -\frac{Q_z}{\rho_a C_p u_* k z} \qquad [51]$$

D. Summary

No calculations have been included following the arguments on the humidity and temperature profiles. Several assumptions should be tested experimentally before any large amount of work is expended in such calculations. Therefore, the assumptions and general form of the model are listed here in anticipation of the brief discussion that concludes this paper. Important assumptions for the general steady-state equation are:

a. The sublimation rate of each windblown snow particle is unaffected by particle interactions.
b. Particles of each size class are distributed with height according to the steady-state theory for uniform particles (where eddy viscosity is equal to particle diffusivity).
c. The logarithmic expression [26] describes the vertical wind profile.

The sublimation rate within a unit volume at some height (z) above a horizontal snow surface then has the general form given by [31] as

$$(dM/dt)_z = N_z \int_0^\infty (dm/dt)_x (z/Z)^{-w/ku_*} f(x) dx$$

A differential equation for the vertical profile of humidity results from the assumptions that:

d. All sublimated vapor is transferred vertically by turbulent exchange.
e. Eddy diffusivity for water vapor is equal to eddy viscosity ($K_w = K_m$).

The humidity profile is obtained by the solution of

$$\frac{d^2\chi}{dz^2} + \frac{1}{z}\frac{d\chi}{dz} + \frac{(dM/dt)_z}{u_* \, k \, f_{sT^z}} = 0$$

Likewise, for temperature, the assumptions are:

f. The heat required for the sublimation process is supplied by radiation, and the vertical transfer by turbulent exchange.

g. The coefficient of turbulent heat exchange is equal to eddy viscosity ($K_h = K_m$).

The differential equation for the vertical profile of temperature is

$$\frac{d^2T}{dz^2} + \frac{1}{z}\left[\frac{dT}{dz} + \right] - \frac{L_s (dM/dt)_z}{\rho_a \, C_p \, u_* \, kz} = \frac{-Q_z}{\rho_a \, C_p \, u_* \, kz}$$

DISCUSSION

The assumptions used to derive a general relationship for sublimation of drifting snow appear quite reasonable, considering the low natural concentrations and the near-neutral stability likely under these strong winds. (The possible exception, in assuming that eddy viscosity equals snow diffusivity, has been noted.) Many of the suppositions made in order to evaluate the general equation, however, present interesting questions for the experimenter.

First, what is the density of a drifting snow particle? Is it equal to that of ice, as assumed in these calculations? If not, then the surface area of a given mass of drifting snow is larger, and the particle fall velocity is less, than predicted here. Answering this question is fundamental to the study of sublimation from drifting snow.

How is particle fall velocity related to particle size? This question involves the answer to the particle density problem, as well as a correlation between particle shape and fall velocity. In this paper the linear relation, $w = C_2 x$, was used to express the fall velocity in terms of shape and size, but the assumption has an important influence on the computed snow concentration profile. Thus, a more accurate approximation would be worthwhile.

What is the actual ventilation velocity of a suspended snow particle? Is it closely approximated by the particle fall velocity, or should the interaction between particle size and the turbulent energy spectrum be included? Related to these questions is the effect of ventilation on small particles ($Re < 10$). Calculations here have used the same particle sublimation rate throughout the size range, but this may overestimate the sublimation of the small particles.

By the arguments presented in this paper the vertical profiles of both humidity and temperature are expected to show the influence of sublimation. Simultaneous profile measurements of humidity, temperature, windspeed and snow concentration under measured conditions of radiation would provide a test of this model. However, several instrumentation problems must be overcome before such measurements are possible.

To assess the hydrologic importance of sublimation from drifting snow within some region another set of questions requires answers. How frequently do strong winds move snow? What temperature and humidity conditions prevail during these events? What proportion of the drifting occurs at night, and, during the day how much solar radiation is received?

Probably the greatest shortcoming of this sublimation model is the steady-state assumptions made in all stages of the development. Hopefully, this work will provide some initial level of understanding, but certainly the unsteady nature of the phenomenon must be accounted for, in a true description of sublimation from wind-transported snow.

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APPENDIX

VALUES OF PHYSICAL PROPERTIES OF AIR AND WATER USED FOR CALCULATIONS

Table of Values at 1000 mb

Temperature, T (°C)	k[1]	L_s[1]	D[2]	$\rho_s(T)$[1]	ν	μ[1]	M	R	M/R
	cal cm^{-1} sec^{-1} $°C^{-1}$	cal g^{-1}	cm^2 sec^{-1}	g cm^{-3}	cm^2 sec^{-1}	g cm^{-1} sec^{-1}	g mol^{-1}	cal $°K^{-1}$ mol^{-1}	g °K cal^{-1}
-0°	$5.80 \cdot 10^{-5}$	677.0	0.206	$4.847 \cdot 10^{-6}$	0.1346	$1.718 \cdot 10^{-4}$	18.0153	1.98583	9.0721
-5°	$5.72 \cdot 10^{-5}$	677.3	.200	$3.246 \cdot 10^{-6}$	.1304	$1.692 \cdot 10^{-4}$			
-10°	$5.63 \cdot 10^{-5}$	677.5	.194	$2.139 \cdot 10^{-6}$	.1259	$1.667 \cdot 10^{-4}$			
-15°	$5.54 \cdot 10^{-5}$	677.7	.187	$1.387 \cdot 10^{-6}$	.1216	$1.641 \cdot 10^{-4}$			
-20°	$5.54 \cdot 10^{-5}$	677.9	.180	$.884 \cdot 10^{-6}$	.1173	$1.615 \cdot 10^{-4}$			

1/ Smithsonian Meteorological Tables (List 1966.)

2/ International Meteorological Tables (WMO-No. 188, TP. 94); taken as 7 percent less than table value.

Table of Variation with Pressure at -20°C

Elevation[1] (km)	P	ρ_a[2]	ν[3]	D[4]	S_o[5]
	mb	kg/m^3	cm^2 sec^{-1}	cm^2 sec^{-1}	cm^{-2} min
0	1000	1.4039	0.1150	0.180	0.8
1	900	1.2635	.1279	.200	1.1
2	800	1.1231	.1439	.225	1.3
	750	1.0549	.1532	.240	1.4
3	700	.9867	.1638	.257	1.46
	650	.9162	.1763	.277	1.53
4	600	.8457	.1908	.300	1.60

1/ Rough estimate from NACA standard atmosphere.

2/ Computed from virtual temperature (see Smithsonian Meteorological Tables (List 1968).)

3/ Computed from $\nu = \mu/\rho_a$.

4/ Computed from standard equation (see text).

5/ A roughly parabolic distribution drawn from Geiger (1965).

LIST OF SYMBOLS

a = $-[1/\kappa u_*] \ln(z'/Z_1)$ a parameter determined by the logarithmic wind profile (sec/cm)

b = major semi-axis of ellipsoid of revolution (cm)

c = minor semi-axis of ellipsoid of revolution (cm)

A = a constant

A_1 = project area of particle perpendicular to direct solar radiation (cm^2)

A_2 = projected area of particle perpendicular to reflected solar radiation from horizontal snow surface

B = a constant

C = electrostatic capacitance (shape factor for mass transfer)

C_{abs} = particle absorbing cross section (cm^2)

C_1 = computational grouping of factors depending on meteorological conditions (g/cm sec)

C_2 = fall velocity shape factor ($2440\ sec^{-1} \leq C_2 \leq 3880\ sec^{-1}$)

C_p = specific heat of air [=0.240 cal/°K (g dry air)]

C_v = coefficient of compressibility

D = diffusivity of water vapor in air (cm^2/sec)

dm/dt) = sublimation rate for a single particle (g/sec)

$m/dt)_x$ = sublimation rate for a particle with diameter x (g/sec)

$M/dt)_C$ = total sublimation rate for an arbitrary column of air and snow (g/sec)

dM/dt) = sublimation rate of mass M of snow in an arbitrary volume (g/sec)

$/dt)_{zx}$ = sublimation rate of the mass of particles M_x with diameters x to (x + dx) in an arbitrary volume at height z (g/sec)

$M/dt)_z$ = sublimation rate for the mass of snow in arbitrary volume at height z, (g/sec)

e = 2.718 . . .

E = vertical flux of water vapor (g/cm sec)

E_{abs} = particle absorbing efficiency

$f(x)$ = general particle size distribution

F = 1/2 (Nu), wind factor

F_m = ventilation factor for mass transfer

F_h = ventilation factor for heat transfer

G = particle geometrical cross section (cm^2)

H = heat flux (cal/cm^2 sec)

κ = von Karman's constant, 0.4

k = thermal conductivity of air (cal/cm sec °K)

k_h = turbulent heat transfer coefficient (cm^2/sec)

k_m = eddy viscosity (cm^2/sec)

k_w = eddy diffusivity for water vapor (cm^2/sec)

L_s = latent heat of sublimation (cal/g)

m = particle mass (g)

M = molecular weight of water (g/mol)

M = mass of snow in an arbitrary volume (g/volume)

M_x = mass of snow with particle diameters, x to (x + dx) in an arbitrary volume (g/volume)

M_{zx} = mass of particles with diameter x to (x + dx) in an arbitrary volume at any height z (g/volume)

M_{Zx} = mass of particles with diameter x to (x + dx) in an arbitrary volume at reference height Z (g/volume)

n = exponent in diffusivity equation (1.75)

N = number of particles in an arbitrary volume

N_z = number of particles in an arbitrary volume at height z

N_Z = number of particles in an arbitrary volume at the reference height

N_{zx} = number of particles with diameter x to (x + dx) in an arbitrary volume at any height z

N_{Zx} = number of particles with diameter x to (x + dx) in an arbitrary volume at reference height Z

(Nu) = Nusselt number (2rK/D)

p = atmospheric pressure (mb)

(Pr) = Prandtl number ($\mu C_p/K$)

P = general function of height

Q = net rate of heat transfer by radiation (cal/sec)

Q = general function of height

r = radius (cm)

R = general function of height

R = universal gas constant (cal/mol °K)

(Re) = Reynolds number (2rV/ν) or (xw/ν)

(RH) = relative humidity used throughout as the water vapor density in percent of the saturation value over a plane surface

(Sc) = Schmidt number ($\mu/\rho_a D$)

(Sh) = Sherwood number (2rK'/D)

S = total solar radiation flux (cal/cm^{2}sec)

T_p = particle surface temperature (°K)

T_s = temperature of horizontal snow surface (°K)

T_v = virtual temperature (°C)

u = instantaneous air velocity (cm/sec)

$\bar{u}$ = mean horizontal wind velocity (cm/sec)

u_p = instantaneous wind velocity

u_r = $(u_p - u)$ relative velocity

u_* = friction velocity $u_* = \sqrt{\tau_o/\rho_a}$ (cm/sec)

$\overline{u^2}$ = mean square horizontal velocity of air (cm^2/sec^2)

v = ventilation velocity of air relative to particle (cm/sec)

w = particle fall velocity (cm/sec)

x = nominal particle diameter [diameter of sphere with equal volume] (cm)

$\bar{x}$ = mean particle diameter

z = height measured from horizontal surface (cm)

z_o = roughness parameter (cm)

Z = reference height (cm)

α = parameter of particle size distribution

β = parameter of particle size distribution (cm)

$\Gamma(\alpha)$ = gamma function in α

ε = eddy viscosity (cm^2/sec)

ζ = particle surface albedo

λ = albedo of horizontal snow surface

μ = micron, 10^{-4} cm

μ = dynamic viscosity (g/cm sec)

ν = kinematic viscosity (cm^2/sec)

ξ = ratio of major to minor semi-axis (b/c) for prolate spheroid

Θ = adiabatic lapse rate (.01°C/m)

π = 3.14 . . .

ρ = water vapor density in the remote environment (g/cm^3)

ρ_a = density of air (g/cm^3)

ρ_p = particle density (g/cm^3)

ρ_r = water vapor density near particle surface (g/cm^3)

ρ_{sT} = saturation density of water vapor at temperature T (g/cm^3)

σ = $(\rho/\rho_{sT} - 1)$ undersaturation of the environment with respect to water vapor [(RH) - 100] = 100σ in percent

τ = turbulent shear stress (dynes/cm^2)

τ_o = surface shear stress (dynes/cm^2)

ϕ = volume fraction of snow in air

$1 - \phi$ = voidage

q = specific humidity

Schmidt, R. A., Jr.
1972. Sublimation of wind-transported snow — a model.
USDA Forest Serv. Res. Pap. RM-90, 24 p. Rocky Mountain Forest and Range Experiment Station, Fort Collins, Colorado 80521.

Sublimation from blowing snow is estimated from the balance of heat and mass transfer on a volume of air and nonuniform ice particles. Size and the distribution of sizes are important particle factors, but fragmented and abraided shapes appear to increase sublimation only slightly above the estimate for spherical particles. Humidity and temperature are the overriding environmental factors, but atmospheric pressure and solar radiation are also important. The effect of turbulence on convection around the particles does not appear important in view of the small particle sizes encountered. Rather, turbulent transfer determines the snow concentration profile, and the gradients of heat and water vapor necessary to balance the sublimation process.

Keywords: Snow density, snow samplers, weather control, evaporation, sublimation

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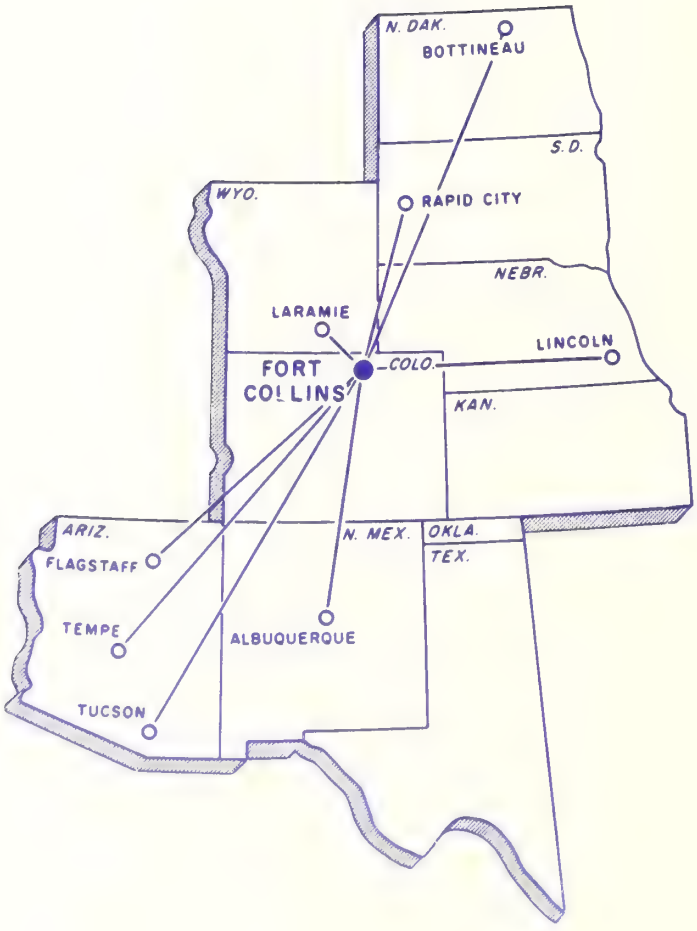
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Collins, Colorado

CLASSIFICATION OF DEER HABITAT IN THE PONDEROSA PINE FOREST OF THE BLACK HILLS, SOUTH DAKOTA

John F. Thilenius

ABSTRACT

The ponderosa pine forest was classified into 13 habitat units by cluster analysis of a similarity matrix based on the vegetation, soil, and site attributes of 100 randomly located sample stands. Habitat units were defined at a minimum similarity of 60 percent. The comparative use of the habitats by deer was evaluated by analysis of variance of long-term (9 years) data on deer pellet group densities in the sample stands.

Keywords: Wildlife management, forest-wildlife relations, synecology, *Pinus ponderosa*.

SDA Forest Service
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May 1972

Classification of Deer Habitat in the Ponderosa Pine Forest of the Black Hills, South Dakota

by

John F. Thilenius, Plant Ecologist

Rocky Mountain Forest and Range Experiment Station[1]

[1]*Central headquarters maintained at Fort Collins in cooperation with Colorado State University; research reported here was conducted at Rapid City, South Dakota, in cooperation with South Dakota School of Mines and Technology. The cooperation of South Dakota Game, Fish, and Parks Department is gratefully acknowledged.* *Author is presently located at Laramie in cooperation with the University of Wyoming.*

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Classification of Deer Habitat in the Ponderosa Pine Forest of the Black Hills, South Dakota

John F. Thilenius

Almost 70 percent of the Black Hills of western South Dakota and eastern Wyoming is covered by forest where *Pinus ponderosa* is the only overstory tree. In 1968, the deer herd using this forest was estimated at over 20,000 animals (Richardson and Schwarting 1969). The majority of these are white-tailed deer (*Odocoileus virginianus dacotensis*), but mule deer (*O. hemionus hemionus*) are also present.

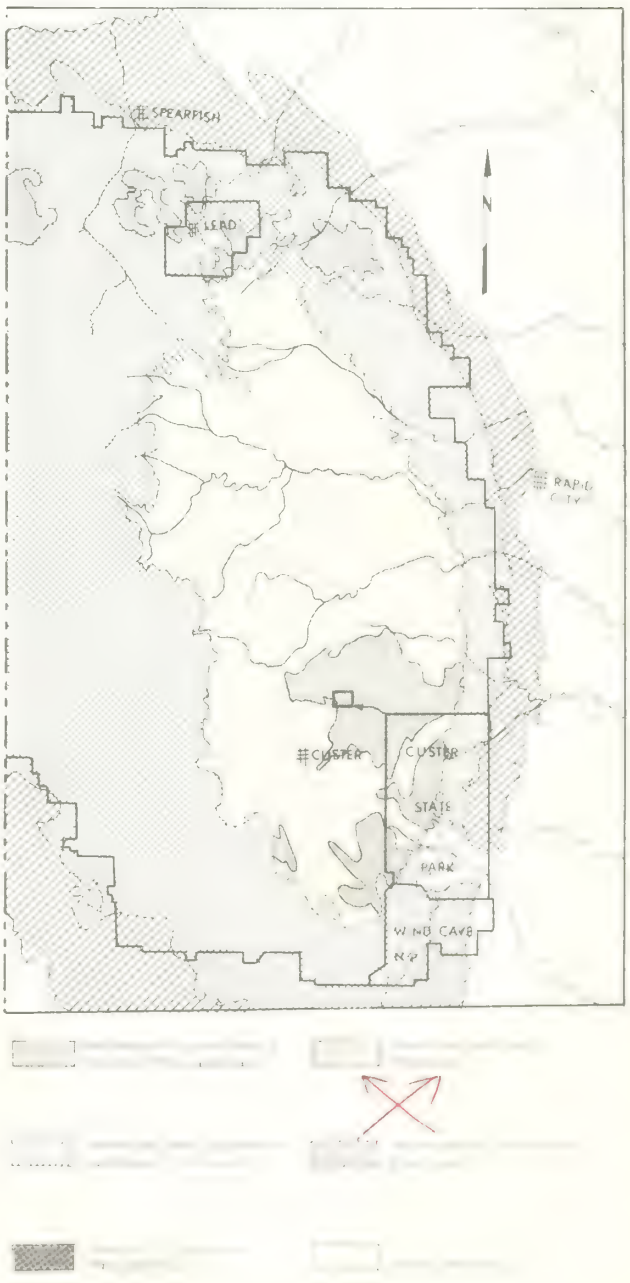
For many years, the South Dakota Game, Fish, and Parks Department has determined deer population trends in the Black Hills by annual counts of deer pellet groups in sample areas distributed throughout the Black Hills National Forest. The wide geographic distribution of these sample areas and the long-term index of deer use on them provided a unique opportunity to define and classify habitats in the ponderosa pine forest, and to evaluate habitat-deer relationships.

STUDY AREA

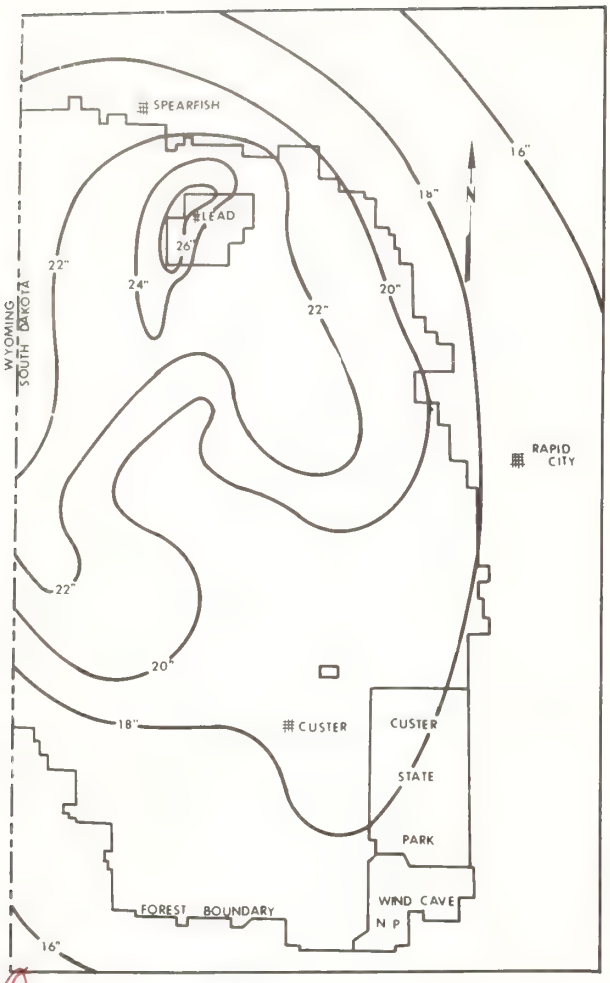
Physiography and Geology

The Black Hills are an elliptically shaped, uplifted dome, over 1.8 million acres in area. The drainage pattern is radial-dendritic, but the majority of the permanent streams flow eastward.

The geology of the Black Hills consists of a series of concentric formations (map 1). The central formation is a region of highly dissected topography composed of metamorphosed Precambrian quartz-mica schists with a general elevation between 4,000 and 5,500 feet. A large amount of surface rock is exposed. Surrounding this is a formation of Paleozoic limestone. The topography here is gently rolling, especially in the northwestern section where the limestone forms a plateau generally above 6,000 feet elevation (map 2). Several points on this plateau exceed 7,000 feet. Along the eastern edge of the Black Hills the same formation rarely exceeds 5,000 feet elevation. Steep cliffs, several hundred feet high, occur along the discontinuity between



Map 1.—Geology of the Black Hills.



Map 2.—Elevation pattern in the Black Hills.

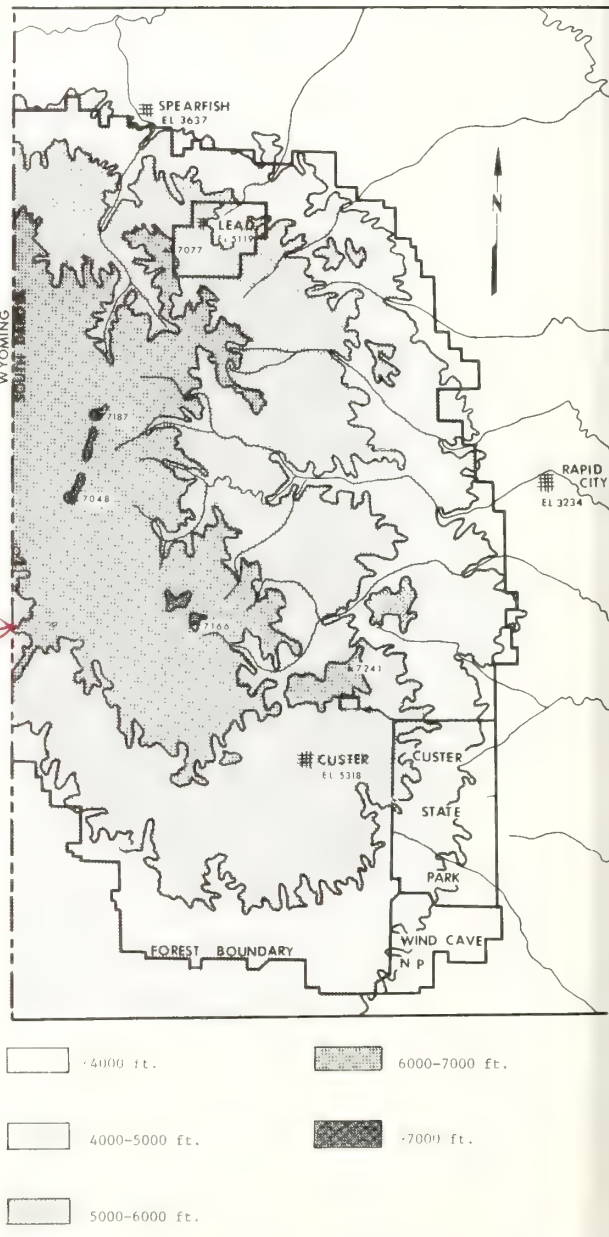
the limestone and adjacent formations, and along river canyons.

There are two major intrusions in the Black Hills. In the south-central portion is an intrusive massif of Precambrian granite weathered into vertical cliffs and rock spires. Harney Peak (7,241 feet), the highest elevation in the Black Hills, is an isolated summit here, but the general elevation is between 5,500 and 6,500 feet. Along the northern edge of the Black Hills are several intrusions of Tertiary acid-igneous rocks which form a rugged topography characterized by barren talus slopes. Terry Peak (7,071 feet) is the highest point in this region; most of the area, however, is between 5,000 and 6,500 feet elevation.

Encircling the periphery of the Black Hills is a region of complex geology. The outer portion of this region is a low, narrow hogback ridge of Mesozoic hard sandstone and shale. Between this hogback ridge and the central mass is a valley formed from reddish color Triassic and Permian soft shale and sandstor This "Red Valley" also almost completely e circles the central mass. Most of this regi is below 4,000 feet elevation.

Climate

The precipitation pattern of the Black Hi is closely related to elevation (maps 2 and Mean annual precipitation is over 26 inch at high elevations in the northern region, b



Map 3.—Precipitation patterns in the Blac Hills.

ss than 18 inches in the foothills and southestern Black Hills (Orr 1959). Most preipitation comes as rain in May, June, and uly, although yearly snowfall may exceed 0 inches at high elevations on the limestone ateau.

The temperature regime is typical of a ntinental climate. Mean annual temperatures the ponderosa pine forest zone are from ° F. to 48° F. with an extreme range of 2° F. to -40° F. Strong temperature inersions are common during the winter, and e temperature at 5,000 feet or higher may be veral degrees above freezing while the temerature at 3,000 feet is in the subzero range.

orest Vegetation

The extent of ponderosa pine forest in the lack Hills generally coincides with the 4,000ot contour, the outer edge of the limestone rmation, and the 18-inch isohyete. There e approximately 1.2 million acres of forest minated solely by *Pinus ponderosa,* and e general appearance of the Black Hills is at of a monoculture of this tree. Almost e entire forest is in a disturbed condition om logging, livestock grazing, mining operaons, wildfire, and fire protection.

Only four other species of arboreal conifers e endemic to the Black Hills. *Picea glauca* mprises about 4 percent of the timber volume. is most abundant at high elevation in the rthern Black Hills and in the granite area ear Harney Peak. In some areas it is an erstory dominant, but more often grows cominant or subordinate to *Pinus ponderosa. inus contorta* var. *latifolia* occurs intermixed ith *Pinus ponderosa* in one 90-acre stand in e central Black Hills. *Pinus flexilis* is present a subordinate tree to *Pinus ponderosa* and *icea glauca* in one isolated 6-acre stand near arney Peak. In the southern Black Hills, *uniperus scopulorum* may be codominant with *inus ponderosa* along the foothills.

Deciduous tree species are poorly repreented in the ponderosa pine forest. Only ree species, *Populus tremuloides, Betula papyfera,* and *Quercus macrocarpa,* are important. *opulus tremuloides,* the most abundant, grows a subordinate tree under the *Pinus ponderosa* nopy, along the ecotone between the forest nd grassland at high elevation in the northern lack Hills, and as a dominant tree on old rest fire burns in the limestone and igneous gions. *Betula papyrifera* is much less abundant an *Populus tremuloides* and is more common on mesic sites. It usually has a multistemmed growth form. *Quercus macrocarpa* occurs both as a tree and as a shrub, along the foothills of the Black Hills.

While the number of species of overstory trees in the Black Hills is limited, the understory is rich in species. Understory shrubs typical of different flora are: *Ostrya virginiana* (Eastern deciduous forest), *Symphoricarpos occidentalis* (Great Plains grassland), *Juniperus communis* (Northern coniferous forest), *Cerco carpus montanus* (Mountain brush-type), *Arctostaphylos uva-ursi* (Western coniferous forest).

Many graminoids (grasses, sedges, and rushes) and forbs are present. The most common graminoids are: *Poa pratensis, Danthonia intermedia, Oryzopsis asperifolia, Andropogon scoparius, Agropyron griffithsi,* and *Carex* spp. Important forbs are *Achillea millefolium, Campanula rotundifolia, Galium biflorum, Antennaria neglecta,* and *Viola adunca.* The legumes *Vicia americana* and *Lathyrus ochroleucus* are also common under the *Pinus ponderosa* canopy.

LITERATURE

Although the taxonomy of Black Hills vegetation has been covered by Rydberg (1932) and McIntosh (1949), there has been very little published on the synecology of the region. Hayward (1928) gave an outline of the plant communities based on the theories of F. E. Clements (1936). All of the ponderosa pine forest was classified in a single category, "western yellow pine association: Rocky Mountain montane forest climax." McIntosh (1949) repeats Hayward's scheme in the plant ecology section of his paper.

In the only other paper dealing directly with synecology in the Black Hills, Leedy and Youngberg [2] described three *Pinus ponderosa* communities and one *Picea glauca* community. Although their work was based entirely on reconnaissance information, they did provide morphological descriptions of the soils underlying these communities.

Radeke and Westin (1963) described three classes of gray wooded soils occurring as the substrate of ponderosa pine forest. These soils have developed from a variety of parent materials. As yet, they have not been correlated or

[2] *Leedy, J.D., and C. T. Youngberg. Coniferous forest communities in the Black Hills, South Dakota. (Unpublished report, Wheaton Coll. Sci. Sta., 8 p., n.d.)*

named. A report from the U.S. Soil Conservation Service (1959) gave detailed information on the field characteristics and chemical-physical properties of the profiles described by Radeke and Westin.

The only study directly concerned with the types of deer habitat in the Black Hills was done by R. R. Hill (1946). He confined his work to the northern section and described seven types of habitat in very general terms. Important browse species occurring in the various types were listed and rated for preference, but no indication of species dominance or abundance was provided, nor was the importance of different types of deer habitat discussed. Hill's classification of Black Hills deer habitat is:

1. Mature or dense ponderosa pine *(Pinus ponderosa).*
2. Open ponderosa pine.
3. Northern white spruce *(Picea glauca).*
4. Birch-Aspen *(Betula papyrifera-Populus tremuloides).*
5. Oak *(Quercus macrocarpa).*
6. Recent burns.
7. Open parks.

The details on the establishment of the pellet group density transects and the sampling procedures used by the South Dakota Game, Fish, and Parks Department are presented in a Pittman-Robertson Job Completion Report (Hart 1957). In 1956, 53 transects (one in each township in the Black Hills National Forest), each 2,000 feet long and 10 feet wide were established. Since initial establishment the length has been decreased to 1,000 feet, the width to 6 feet, and the number of transects doubled. Six transects have been abandoned because they have been heavily grazed by sheep or logged.

At the time of establishment, data were collected on slope aspect, slope angle, overstory type (pine, deciduous, open, pine-deciduous, pine-deciduous-spruce, doghair pine), understory type (grass, browse, forbs, litter, or any combination of these four), and percent ground visibility (poor, 0-24 percent; fair, 25-49 percent; good, 50-74 percent; excellent, 75-100 percent) of each 100-foot segment. These data have been misplaced and were not available.

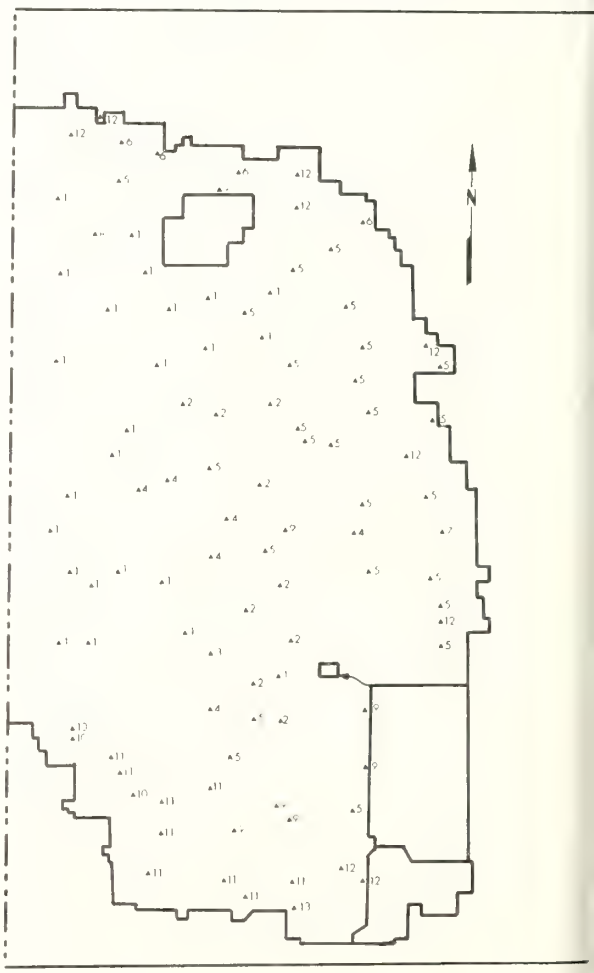
A summary of this preliminary data in the report indicated (1) no relationship between pellet group density and overstory type of ground visibility; (2) a weak relationship between pellet ground density and understory type, with the browse type having the highest use; (3) a preference for southerly slopes with low angles (0-10 percent). These conclusions were based on only a single year's sample a some of the categories used, for example, brow type, are vague.

Other literature pertinent to methods a techniques are given in the appropriate sectio

METHODS

Field Sampling

The ponderosa pine forest was sampled 100 locations within the Black Hills Natio Forest (map 4). All sample sites were locat on transects used by the South Dakota Depa ment of Game, Fish, and Parks to determi the size of the Black Hills deer herd by annu counts of deer pellet group densities. T transects, established several years prior to t start of this study by Department personn



Map 4.—Location of sample stands in th Black Hills National Forest.

ere located in a restricted random manner, ro in each survey township within the boun- ries of the Black Hills National Forest.

Each treatment is a belt of one hundred x 10-foot plots (total length 1,000 feet). egetation, soil, and site vary considerably thin these long belt transects. To minimize is variation, a homogeneous area representa- ve of the most predominant habitat crossed the transect was selected in the field as e location for the samples used in this study.

A 60- x 100-foot macroplot was established the selected location by measuring a randomly lected distance (to the nearest 10 feet) from e starting point of the transect. This distance as restricted so the macroplot was within e selected area. Each macroplot represents relatively homogeneous, independent, random mple of the vegetation, soil, and site attributes the ponderosa pine forest on which there a long-term index of the intensity of er use.

Three randomly located plots 10 x 100 feet ere established within the macroplot to sub- mple the floristic attributes. On each of ese, the frequency of graminoids, forbs, low rubs (< 1.5 feet tall), and tree seedlings < 0.5 foot tall) was recorded on one hundred foot-square quadrats arranged in a belt ansect along the centerline of the plot. The equency of tall shrubs (> 1.5 feet tall) was corded on a belt transect of twenty-five 4- x oot quadrats coincident with the belt transect 1-foot-square plots. Trees were sampled dividing the 10- x 100-foot plot into ten - x 10-foot quadrats and recording the fre- ency by 4-inch d.b.h. (stem diameter at 4.5 et above the ground surface) classes. Plot zes were selected to give average frequencies tween 20 and 80 percent for the most fre- ent taxa (Hyder et al. 1965). Frequency ta from all three plots were combined for alysis.

A soil pit was excavated near the center the macroplot and the soil described to the andards of the U.S. Soil Survey (U.S. Bur. ant Indus., Soils and Agr. Eng. 1951). The evation, slope aspect, slope angle, position the slope, relief features, and percentage ground surface covered by rock, litter, and re ground were recorded for each macroplot. he presence of natural and man-caused in- ences such as fire, wildlife, logging, grazing, ning, and so forth, was also recorded. Geo- gical formations were determined by refer- ce to Darton's (1951) geological map of the ack Hills and from the material excavated from the subsurface horizons (C and R) of the soil. The precipitation regime was established by reference to Orr (1959).

Analytical Methods

The synecological units of the ponderosa pine forest were determined by grouping the sample plots into sets whose members were similar in vegetation, soil, and site attributes. Table 1 gives the analytical attributes utilized, their units of measurement, and method of encoding. To determine similarity, a numerical cluster analysis procedure was used. The essentials of this program are as follows:

1. An rxc table is prepared with the attribute data as the rows (r) and the sample plots as the columns (c).
2. The diverse attribute data are standardized by setting the maximum attribute value for each row equal to 100 and scaling all other values accordingly: that is, all data are transformed to a relative proportion of the maximum value, and thus become additive.
3. An initial matrix of similarity is computed between all possible combinations of sample plots. Sorensen's (1948) coefficient of similarity, $K = (2c/a+b)\ 100$ is used as the index of similarity. In this formula, "a" is the sum of all standardized attribute data for one sample plot, "b" is this sum for another sample plot, and "c" is the sum of the lower value for each attribute common to the two sample plots. The range of K is 0 to 100, with 100 equal to complete similarity. Bray and Curtis (1957) sampled the same area repeatedly, and found the average value of K to be 82. They concluded that because of sampling error, maximum K is approximately 80 to 85 instead of 100.
4. The initial matrix of similarity is subjected to cluster analysis by the weighted pair-group method (Sokal and Sneath 1963) as follows:

   a. The two sample plots in the matrix having the highest similarity are selected and combined into a single unit or cluster.
   b. A new matrix of similarity is computed between this cluster and the remaining unclustered sample plots. A simple average, $K = K_{ij} + K_{hj}/2$, replaces the two K values of the clustered sample plots. K_{ij} equals the index of similarity between one member (i) of the established

Table 1.--Attribute coding for computer analysis

A. Vegetation
1. Frequency of overstory trees (by species and d.b.h. class) in percent.
2. Frequency of large shrubs (by species) in percent.
3. Frequency of small shrubs, grasses, sedges, and forbs (by species) in percent.

B. Soil
1. Number of mineral horizons present.
2. Depth of solum in inches.
3. Thickness of the O1 horizon (litter) in inches.
4. Thickness of the O2 horizon (humus) in inches.
5. Thickness of the A1 horizon in inches.
6. Hue of the A1 horizon, scaled to give the highest value to red and the lowest to yellow.
   a. 10R = 64
   b. 2.5YR = 32
   c. 5YR = 16
   d. 7.5YR = 8
   e. 10YR = 4
   f. 2.5Y = 2
   g. 5Y = 1
7. pH of the A1 horizon to the nearest 0.1 pH unit (electrometrically determined).
8. Texture of the A1 horizon specified by a particle size "ratio-of 10" derived by rounding off the average percentage of sand (2.0mm - 0.05mm), silt (0.05mm - 0.002mm), and clay (-0.002mm) in the 12 textural classes given in the Soil Survey Manual (1951). The sum of the numerals equals 10 in all classes.
   a. Sand = 910
   b. Loamy sand = 811
   c. Sandy clay loam = 712
   d. Sandy loam = 541
   e. Sandy clay = 514
   f. Loam = 442
   g. Clay loam = 334
   h. Silt = 181
   i. Silt loam = 172
   j. Silty clay loam = 163
   k. Silty clay = 154
   l. Clay = 118
9. Percentage of coarse fragments (+2mm) in the A1 horizon.
10. Effervescence with HCl of the A1 horizon.
    a. Violent 8
    b. Strong 4
    c. Slight 2
11. Thickness of the A2 horizon (eluviation zone) in inches.
12. Hue of the A2 horizon (see Item 6).
13. pH of the A2 horizon (see Item 7).
14. Texture of the A2 horizon (see Item 8).
15. Percentage of coarse fragments in the A2 horizon.
16. Effervescence with HCl of the A2 horizon (see Item 10).
17. Thickness of the B2 horizon (illuviation zone) in inches.
18. Hue of the B2 horizon (see Item 6).
19. pH of the B2 horizon (see Item 7).
20. Texture of the B2 horizon (see Item 8).
21. Percentage of coarse fragments in the B2 horizon.
22. Effervescence of the B2 horizon (see Item 10).
23. Hue of the C horizon (see Item 6).
24. pH of the C horizon (see Item 7)
25. Texture of the C horizon (see Item 8).
26. Percentage of coarse fragments of the C horizon.
27. Effervescence of the C horizon (see Item 10).

C. Site
1. Slope aspect in degrees from true north.
2. Slope angle in percent.
3. Elevation in feet.
4. Position in percentage of slope below the nearest ridge.
5. Macrorelief of general area.
   a. Level = 0
   b. Undulating = 5
   c. Rolling = 15
   d. Hilly = 30
   e. Steep = 50
6. Microrelief in immediate vicinity of plot.
   a. Concave = 1
   b. Flat = 2
   c. Convex = 3
7. Percentage of ground covered by rocks.
8. Percentage of ground covered by litter.
9. Percentage of bare ground.

cluster (i+h) and an unclustered sample plot (j), and K_{hj} is equal to this index for the other member of the established cluster.

c. Steps "a" and "b" above are repeated until all sample plots have been clustered.

The results of cluster analysis are presented in a dendrogram (fig. 1). The vertical axis of the dendrogram merely separates the sample plots and has no scale. The horizontal axis is scaled in units of K (percentage similarity). Junction points between stems along the horizontal axis indicate the sample plots to the left of the junctions are alike at the K value shown on the horizontal axis scale.

The number of groups of sample plots to be designated is determined by drawing a line across the dendrogram parallel to the vertical axis at a designated level of K. The number of stems cut by this line indicates the number of units present. In this paper these units are called "Habitat Units" (hereafter abbreviated "HU").

The level of K at which HU are designated is variable and depends primarily on the use to which the classification is to be put and the ecosystem under consideration (West 1966). Mathematical or statistical tests to determine significant gaps in continuity are not yet available, and the usual statistical tests of signi cance are not applicable (Sokal and Snea 1963). Whatever level of K is selected, it mu be applied uniformly across the whole dendr gram; in other words, it is not permissib to designate one HU at K = 60 and anoth at K =70 (Sneath 1962).

RESULTS

The similarity relationships of the 100 stan sampled are shown in figure 1. This dendr gram is based on 334 attributes of vegetatio soil, and site, and is arranged so the stan occurring at high elevation in the central a northern Black Hills are uppermost.

Habitat Units have been designated at tw levels of similarity. These are K>54 and K> At K>54 (54 percent minimum internal sim larity in vegetation, soil, and site attribute three HU are present.

HU-A (40 stands) is found in the hig elevation, moist region of the northwestern a western Black Hills. The ponderosa pine for understory here has well-developed shrub a herb strata composed of mesophytic taxa, ma of which are present at high frequency.

HU-B (31 stands) occurs at intermediate low elevations in the northeastern and cent

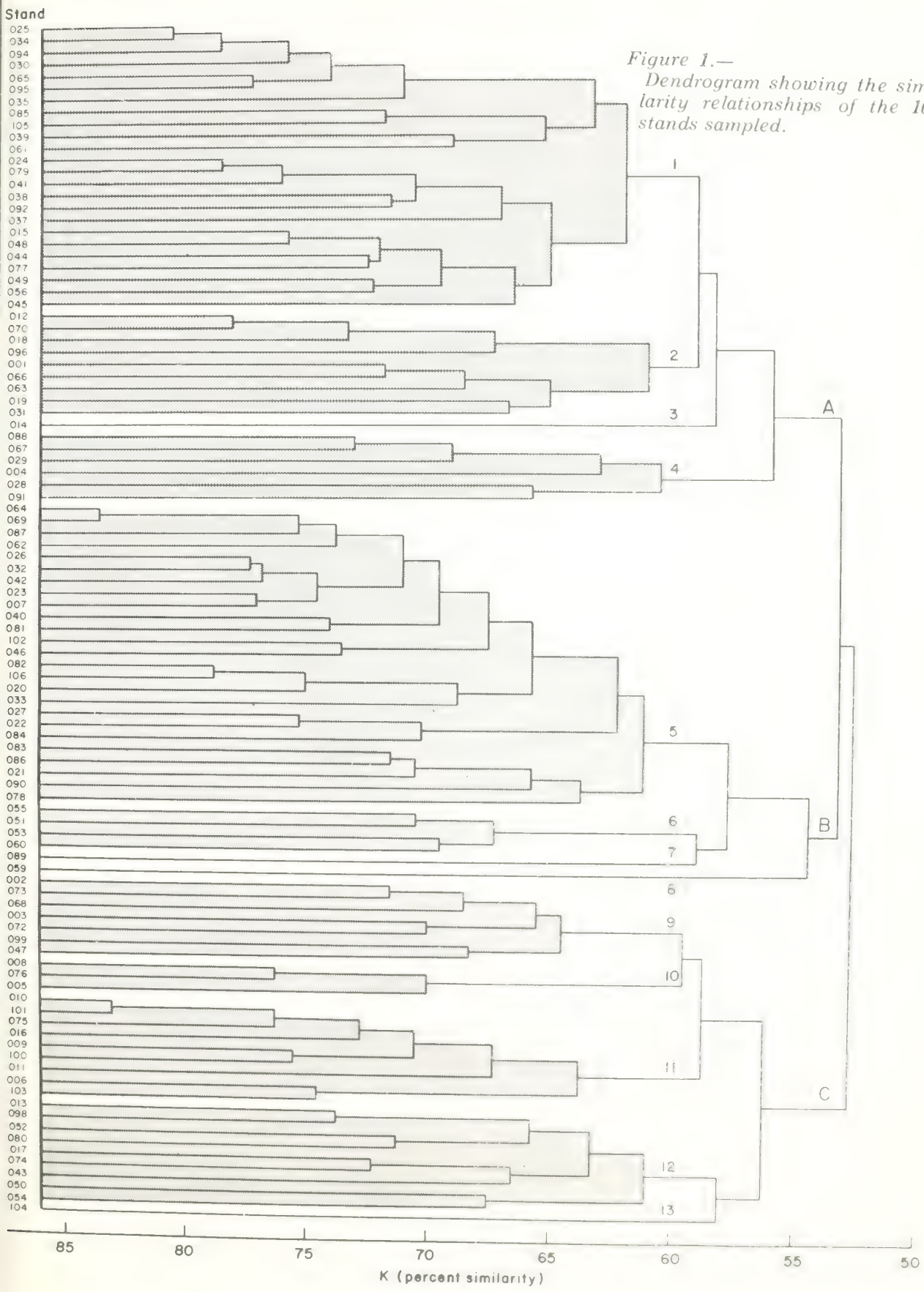


Figure 1.— Dendrogram showing the similarity relationships of the 100 stands sampled.

part of the Black Hills. Shrubs are still the most important taxa in the understory, but the more mesophytic taxa are much less frequent and a number of xerophytic taxa with prairie affinities are present.

HU-C (29 stands) is present along the northern foothills and in the relatively low-elevation region of the southern Black Hills. Graminoids are the most frequent taxa in the forest understory. Many forbs with prairie affinities are present, and shrub taxa tend to be those adapted to xeric environments.

While the HU designated at K>54 can b related in a general manner to the gross eco logical and geographic features of the Blac Hills, they are highly variable in taxa composi tion and other attributes. Since HU can b designated at any level of similarity, the in ternal homogeneity of HU is increased by rais ing the value of K. The rule followed is t select a level of similarity which maximize the number of HU containing three or mor sample stands. In HU with several stands the range of within-HU attribute variabilit

Table 2.--Percent constancy (C), average percent frequency (F), and maximum percent frequency (M) of major taxa[1] in the habitat units (HU) defined at K≥60, with number of stands (n)

Taxa[2]	HU-1 (n=24)			HU-2 (n=9)			HU-3 (n=1)			HU-4 (n=6)			HU-5 (n=25)		
	C	F	M	C	F	M	C	F	M	C	F	M	C	F	M
	Percent														
OVERSTORY STRATUM															
Pinus ponderosa															
<4 inches d.b.h.	92	30	87	100	55	87	--	10	--	67	14	53	100	62	100
4-8 inches d.b.h.	88	20	50	100	22	73	--	76	--	67	8	17	88	30	90
8-12 inches d.b.h.	83	11	30	67	5	13	--	10	--	67	10	43	64	8	37
>12 inches d.b.h.	75	10	27	33	3	10	--	--	--	17	1	3	32	2	13
[illegible]															
<4 inches d.b.h.	9	6	73	--	--	--	--	--	--	--	--	--	--	--	--
4-8 inches d.b.h.	21	4	53	--	--	--	--	--	--	--	--	--	--	--	--
Populus tremuloides															
<4 inches d.b.h.	54	10	37	44	14	67	--	--	--	17	1	3	20	5	47
4-8 inches d.b.h.	42	4	53	22	1	7	--	--	--	--	--	--	8	-1	3
Betula papyrifera															
<4 inches d.b.h.	--	--	--	22	2	10	--	--	--	--	--	--	12	1	7
4-8 inches d.b.h.	--	--	--	11	-1	3	--	--	--	--	--	--	--	--	--
Quercus macrocarpa															
<4 inches d.b.h.	--	--	--	--	--	--	--	--	--	--	--	--	12	2	7
4-8 inches d.b.h.	--	--	--	--	--	--	--	--	--	--	--	--	12	1	10
8-12 inches d.b.h.	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
>12 inches d.b.h.	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Juniperus scopulorum															
<4 inches d.b.h.	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
TALL SHRUB STRATUM															
[illegible]	83	27	95	22	-1	3	--	56	--	50	4	12	56	6	36
Shepherdia canadensis[3]	58	6	56	67	14	47	--	66	--	--	--	--	56	6	52
Potentilla fruticosa	13	-1	4	--	--	--	--	85	--	--	--	--	4	-1	1
Symphoricarpos occidentalis	--	--	--	22	2	15	--	--	--	100	42	84	--	--	--
[illegible]	46	8	40	44	5	24	--	--	--	17	-1	1	60	8	72
Ostrya virginiana	--	--	--	--	--	--	--	--	--	--	--	--	8	-1	1
[illegible]	--	--	--	--	--	--	--	--	--	--	--	--	24	1	17
Corylus cornuta	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
[illegible]	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Rhus trilobata	--	--	--	--	--	--	--	--	--	--	--	--	12	-1	3
LOW SHRUB STRATUM															
[illegible]	100	44	90	100	46	69	--	60	--	50	22	51	100	29	82
Rosa fendleri	96	20	49	100	23	59	--	22	--	100	20	39	80	13	67
Amelanchier alnifolia[5]	83	14	50	100	10	23	--	4	--	67	2	7	84	12	44
Spiraea lucida	63	18	66	78	16	49	--	--	--	33	1	4	68	17	65
Ribes inebrians	8	1	23	22	-1	3	--	--	--	67	-1	1	20	-1	11
[illegible]	--	--	--	--	--	--	--	--	--	--	--	--	28	6	85
[illegible]	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--

[1] All overstory species plus understory taxa with at least 67 percent constancy in a multistand HU or 20 percent frequency in a single-stand HU.

[2] Indicator taxa for each HU are underlined.

[3] Growing as a low shrub in HU-5.

[4] Growing as a low shrub in HU-12.

[5] Growing as a tall shrub in HU-2.

can be determined, and constancy[3] values for attributes can be computed. For the ponderosa pine forest a level of K > 60 best fits this rule.

[3] *Constancy is a relative expression of the presence and absence of a species in different stands of a community type, based on equal area samples. Frequency is a statistical expression of the representation (presence or absence) of a species in a series of subsamples within a given stand (Cain and Castro 1959).*

At K>60, 13 HU can be defined (fig. 1). The following section contains brief descriptions of each of the HU. It proceeds from the most mesic to the most xeric—from top to bottom on the dendrogram (fig. 1). The HU are designated serially from 1 to 13 and by a multinomial formed from the scientific names of indicator taxa in the overstory, tall-shrub, low-shrub, and herb strata. Table 2 gives the percent constancy and average and maximum percent frequencies for the major taxa in each HU.

U-6 (n=4)			HU-7 (n=1)			HU-8 (n=1)			HU-9 (n=7)			HU-10 (n=3)			HU-11 (n=9)			HU-12 (n=9)			HU-13 (n=1)		
	F	M	C	F	M	C	F	M	C	F	M	C	F	M	C	F	M	C	F	M	C	F	M
														Percent									
0	22	43	--	10	--	--	44	--	100	17	47	100	9	20	100	29	64	89	18	43	--	-1	--
0	17	27	--	43	--	--	7	--	100	17	37	67	8	17	89	17	27	78	7	23	--	--	--
5	13	27	--	7	--	--	13	--	57	10	37	33	2	7	89	13	27	33	2	10	--	--	--
0	8	20	--	--	--	--	--	--	29	3	13	67	2	3	56	4	13	33	1	13	--	--	--
-	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
-	--	--	--	--	--	--	--	--	--	--	--	--	--	-	--	--	--	--	--	--	--	--	-
-	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	-	--
-	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	11	1	10	--	--	--
-	--	--	--	--	--	--	7	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
-	--	--	--	--	--	--	--	--	--	--	--	--	-	--	--	--	-	--	--	--	--	--	--
0	53	90	--	23	--	--	--	--	--	--	--	--	--	--	--	--	--	56	8	20	--	--	--
0	3	7	--	7	--	--	--	--	--	--	--	--	--	--	--	--	--	11	6	3	-	--	--
-	--	--	--	10	--	--	--	--	--	--	--	--	--	--	-	--	--	--	--	--	--	--	--
-	--	--	--	3	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
-	--	--	--	--	--	--	--	--	--	--	--	100	13	20	22	4	27	11	-1	1	--	-	-
0	2	9	--	--	--	--	8	--	--	--	--	33	3	7	--	--	--	22	4	9	--	--	-
-	--	--	--	--	--	--	57	--	14	1	7	--	--	--	--	--	--	11	-1	3	--	--	--
-	--	--	--	--	--	--	8	--	--	--	--	--	--	-	--	--	-	--	--	--	--	--	--
5	2	8	--	1	--	--	--	--	43	13	76	--	--	--	-	--	--	33	22	100	--	--	--
0	66	83	--	54	--	--	77	--	28	8	43	33	8	24	--	--	--	78	29	88	--	--	--
5	5	20	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	11	-1	1	--	--	--
0	42	79	--	13	--	--	--	--	--	--	--	--	--	--	--	--	--	44	7	35	--	--	--
5	3	11	--	--	--	--	31	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	-
-	--	--	--	--	--	--	--	--	--	--	--	100	85	87	22	14	75	--	--	--	--	--	-
-	--	--	--	--	--	--	--	--	--	--	--	100	10	20	44	3	9	11	-1	1	--	-	-
0	56	81	--	69	--	--	36	--	57	25	84	100	27	57	67	21	60	56	13	63	--	-	-
5	2	5	--	--	--	--	25	--	57	19	56	100	3	2	78	4	22	89	5	17	-	--	--
0	37	69	--	2	--	--	87	--	43	4	16	33	1	3	33	2	13	56	15	46	--	--	--
0	25	36	--	13	--	--	36	--	14	-1	2	--	--	--	--	--	--	--	2	12	--	--	--
-	--	--	--	--	--	--	8	--	29	1	7	67	5	7	22	3	1	--	--	--	--	--	--
0	15	39	--	--	--	--	--	--	--	--	--	--	--	--	11	-1	-1	67	6	11	--	--	--
-	--	--	--	--	--	--	--	--	--	--	--	67	-1	1	11	-1	-1	33	7	41		--	-

Table 2.--Percent constancy (C), average percent frequency (F), and maximum percent frequency (M) of major taxa[1] in the habitat units (HU) defined at K≥60, with number of stands (n)--Continued

Taxa	HU-1 (n=24)			HU-2 (n=9)			HU-3 (n=1)			HU-4 (n=6)			HU-5 (n=25)		
	C	F	M	C	F	M	C	F	M	C	F	M	C	F	M
	Percent														
HERB STRATUM															
Shrubs															
Berberis repens	96	42	98	--	--	--	--	--	--	--	--	--	--	--	--
Arctostaphylos uva-ursi	92	47	91	100	56	91	--	--	--	17	8	48	88	39	87
[illegible] (seedlings)	71	4	56	100	4	10	--	--	--	83	1	3	100	9	30
Toxicodendron radicans	--	--	--	--	--	--	--	--	--	--	--	--	20	3	34
Artemisia frigida	--	--	--	22	6	48	--	--	--	33	3	17	8	-1	4
Graminoids															
Oryzopsis asperifolia	83	27	75	78	5	13	--	--	--	50	7	41	60	13	52
Danthonia intermedia	83	19	85	78	40	80	--	--	--	67	18	50	92	14	71
Poa pratensis	71	18	87	56	6	33	--	2	--	100	74	98	52	4	44
Carex concinna	71	7	29	67	7	25	--	--	--	--	--	--	80	15	83
Agropyron griffithsi	50	4	24	78	16	50	--	--	--	--	--	--	40	3	22
Carex foenea	63	10	67	67	24	70	--	--	--	17	-1	1	24	2	22
Bromus inermis	17	2	20	22	2	21	--	21	--	17	6	36	8	1	9
Carex heliophila	29	4	58	56	5	21	--	--	--	67	23	62	40	7	44
Stipa viridula	38	2	16	11	1	7	--	--	--	67	5	10	8	-1	6
Schizachne purpurascens	8	-1	4	22	1	8	--	--	--	--	--	--	4	-1	1
Koeleria cristata	17	-1	4	56	6	16	--	--	--	--	--	--	36	1	14
[illegible]	-	--	--	44	1	7	--	--	--	33	-1	2	44	7	56
Bouteloua curtipendula	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Agropyron smithii	4	1	16	--	--	--	--	--	--	33	4	13	8	1	13
Bouteloua gracilis	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Forbs															
Achillea millefolium	100	25	52	100	18	27	--	8	--	100	37	55	88	9	37
Fragaria vesca	100	26	57	89	16	33	--	34	--	100	12	29	68	6	36
Galium biflorum	100	22	58	89	6	13	--	20	--	67	20	52	64	3	23
Viola adunca	100	8	23	67	9	34	--	4	--	67	4	8	68	2	7
Vicia americana	96	10	29	22	1	7	--	--	--	67	8	31	36	2	14
Lathyrus ochroleucus	88	22	65	67	5	14	--	--	--	83	5	14	44	7	31
Campanula rotundifolia	88	3	13	100	6	13	--	--	--	67	4	9	76	3	12
Zizia aptera	79	6	17	44	2	9	--	-1	--	50	1	3	28	-1	7
Antennaria neglecta	79	4	18	100	11	21	--	--	--	100	10	16	84	5	30
Thermopsis rhombifolia	--	--	--	44	18	74	--	--	--	--	--	--	--	--	--
Erigeron subtrinervis	75	6	34	44	5	22	--	17	--	50	11	39	32	3	17
Lupinus argenteus	71	7	29	--	--	--	--	--	--	--	--	--	--	--	--
Monarda fistulosa	71	6	33	56	8	50	--	--	--	67	7	16	48	2	18
Aster laevis	67	6	28	56	8	25	--	--	--	--	--	--	44	2	20
Apocynum androsaemifolium	54	2	11	100	11	26	--	--	--	33	-1	1	84	6	34
Solidago occidentalis	29	1	10	78	8	22	--	--	--	--	--	--	68	4	40
Anemone patens	42	2	23	67	3	9	--	11	--	67	1	3	56	2	14
Astragalus alpinus	50	6	39	44	2	9	--	21	--	50	11	49	44	3	36
Clematis hirsutissima	13	3	52	--	--	--	--	21	--	--	--	--	4	-1	22
Solidago nemoralis	17	2	28	--	--	--	--	--	--	67	10	27	24	-1	5
Potentilla hippiana	8	-1	3	--	--	--	--	--	--	67	5	29	4	-1	3
Iris missouriensis	13	1	13	--	--	--	--	--	--	67	3	16	--	--	--
Antennaria rosea	54	1	8	56	4	22	--	--	--	67	1	5	52	1	7
Smilacina stellata	33	2	30	33	1	10	--	1	--	50	2	22	60	4	23
Maianthemum canadense	8	-1	3	--	--	--	--	--	--	--	--	--	--	--	--
Sanicula marilandica	13	-1	8	--	--	--	--	--	--	--	--	--	4	-1	1
Lupinus parviflorus	--	--	--	--	--	--	--	--	--	--	--	--	12	-1	2
Artemisia ludoviciana	38	5	24	--	--	--	--	--	--	50	15	46	12	-1	13
Phlox hoodii	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Zygadenus elegans	29	1	17	--	--	--	--	--	--	--	--	--	44	-1	5
Hymenoxys acaulis	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Musineon divaricatum	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Grindelia squarrosa	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Leucocrinum montanum	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Geum triflorum	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Phlox alyssiofolia	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Polygala alba	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Echinacea angustifolia	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Chrysopsis villosa	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--

[1] All overstory species plus understory taxa with at least 67 percent constancy in a multistand HU or 20 percent frequency in a single-stand HU.

[2] Indicator taxa for each HU are underlined.

-6 (n=4)		HU-7 (n=1)			HU-8 (n=1)			HU-9 (n=7)			HU-10 (n=3)			HU-11 (n=9)			HU-12 (n=9)			HU-13 (n=1)		
F	M	C	F	M	C	F	M	C	F	M	C	F	M	C	F	M	C	F	M	C	F	M
73	82	--	--	--	--	34	--	--	--	--	--	--	--	--	--	--	11	1	7	--	--	--
1	4	--	--	--	--	24	--	43	14	37	33	-1	-1	33	1	6	11	2	19	--	--	--
12	29	--	9	--	--	-1	--	86	5	19	33	-1	1	78	9	25	78	5	19	--	-1	--
4	5	--	--	--	--	2	--	--	--	--	--	--	--	11	-1	-1	44	1	3	--	--	--
--	--	--	--	--	--	--	--	43	5	18	100	9	17	22	6	33	11	2	17	--	27	--
34	70	--	--	--	--	--	--	14	1	7	--	--	--	--	--	--	22	4	37	--	--	--
26	60	--	--	--	--	6	--	100	40	59	--	--	--	11	5	41	33	2	11	--	--	--
20	67	--	18	--	--	52	--	100	59	99	67	1	3	33	5	23	56	40	98	--	--	--
1	5	--	--	--	--	-1	--	43	7	29	33	2	7	33	1	7	11	-1	3	--	--	--
-1	1	--	--	--	--	14	--	71	8	39	100	24	46	--	--	--	44	2	11	--	--	--
16	34	--	75	--	--	1	--	57	11	41	67	11	20	67	17	72	33	4	25	--	--	--
--	--	--	--	--	--	--	--	14	-1	3	--	--	--	--	--	--	11	-1	5	--	--	--
12	37	--	--	--	--	--	--	43	1	4	--	--	--	22	-1	2	22	2	10	--	2	--
--	--	--	--	--	--	--	--	--	--	--	33	-1	-1	67	13	38	56	6	29	--	--	--
--	--	--	62	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
--	--	--	--	--	--	--	--	100	16	26	100	14	20	89	4	16	44	4	18	--	12	--
2	6	--	--	--	--	1	--	14	4	28	100	38	57	100	37	82	78	36	85	--	79	--
--	--	--	--	--	--	--	--	14	2	10	100	19	36	56	2	7	11	2	16	--	24	--
--	--	--	--	--	--	--	--	--	--	--	--	--	--	56	26	84	22	1	6	--	--	--
--	--	--	--	--	--	--	--	--	--	--	33	1	4	--	--	--	22	2	15	--	68	--
10	23	--	-1	--	--	15	--	100	12	15	100	3	4	78	5	13	44	5	34	--	--	--
2	4	--	--	--	--	--	--	29	1	6	33	-1	-1	44	2	6	--	--	--	--	--	--
4	10	--	21	--	--	55	--	57	7	28	67	4	10	44	3	16	44	6	26	--	--	--
5	10	--	--	--	--	33	--	57	1	2	33	-1	-1	44	2	8	44	-1	2	--	1	--
5	7	--	3	--	--	34	--	29	1	5	33	2	5	67	7	16	11	-1	6	--	--	--
11	31	--	6	--	--	3	--	14	-1	2	--	--	--	--	--	--	44	2	12	--	--	--
1	3	--	-1	--	--	5	--	71	4	11	67	-1	-1	67	2	4	56	1	7	--	3	--
-1	1	--	--	--	--	1	--	14	-1	2	--	--	--	44	2	12	--	--	--	--	--	--
1	2	--	-1	--	--	12	--	57	2	10	33	-1	-1	22	1	10	33	-1	3	--	--	--
--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
2	4	--	--	--	--	5	--	29	5	37	--	--	--	--	--	--	22	-1	1	--	--	--
--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
12	33	--	--	--	--	48	--	71	1	5	--	--	--	11	-1	-1	56	2	7	--	--	--
-1	1	--	--	--	--	12	--	29	4	19	67	-1	1	44	1	7	11	-1	5	--	--	--
2	5	--	2	--	--	15	--	57	4	21	--	--	--	11	-1	1	33	4	24	--	--	--
--	--	--	-1	--	--	8	--	86	2	7	100	7	8	67	10	32	44	-1	3	--	--	--
--	--	--	--	--	--	--	--	14	2	10	33	-1	-1	11	-1	4	--	--	--	--	--	--
--	--	--	--	--	--	3	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
--	--	--	--	--	--	--	--	71	5	14	--	--	--	11	1	8	33	1	5	--	--	--
--	--	--	--	--	--	--	--	14	-1	1	--	--	--	--	--	--	22	-1	3	--	--	--
--	--	--	-1	--	--	--	--	29	5	3	33	-1	1	--	--	--	--	--	--	--	--	--
1	4	--	--	--	--	--	--	71	4	20	67	3	7	78	2	5	11	-1	-1	--	--	--
3	6	--	44	--	--	20	--	43	5	30	33	2	7	--	--	--	33	-1	9	--	--	--
4	11	--	--	--	--	11	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
2	5	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
-1	2	--	--	--	--	--	--	29	3	11	33	-1	1	56	2	13	11	2	17	--	--	--
--	--	--	--	--	--	3	--	43	3	10	100	18	27	56	2	22	78	11	44	--	--	--
--	--	--	--	--	--	--	--	--	--	--	67	7	14	11	-1	1	--	--	--	--	--	--
--	--	--	--	--	--	--	--	29	-1	2	67	5	13	--	--	--	--	--	--	--	--	--
--	--	--	--	--	--	--	--	--	--	--	100	2	3	33	2	8	22	3	25	--	16	--
--	--	--	--	--	--	--	--	--	--	--	67	4	7	33	-1	2	--	--	--	--	--	--
--	--	--	--	--	--	--	--	--	--	--	67	1	1	--	--	--	--	--	--	--	--	--
--	--	--	--	--	--	--	--	--	--	--	67	1	1	78	2	5	--	--	--	--	--	--
--	--	--	--	--	--	--	--	--	--	--	67	-1	1	--	--	--	--	--	--	--	--	--
--	--	--	--	--	--	--	--	14	1	8	--	--	--	67	6	19	--	--	--	--	--	--
--	--	--	--	--	--	--	--	--	--	--	--	--	--	11	-1	5	--	--	--	--	22	--
--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	26	--
--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	20	--

HU-1: *Pinus ponderosa/Juniperus communis/ Symphoricarpos albus/Berberis repens* **(fig. 2).**

HU-1 is found on the limestone plateau of the northwestern and western Black Hills (map 4). The average elevation of the 24 sample stands is 6,315 feet (range: 5,675 to 6,775 feet). Most of the stands occur between the 22- and 24-inch isohyets, which makes this the most mesic HU of the ponderosa pine forest.

The relatively high constancy and frequency of all sizes classes of *Pinus ponderosa* indicates this HU provides good growing conditions for this species. The presence of *Picea glauca* and *Populus tremuloides* in many stands is a further indication of the mesic nature of this HU.

The understory in most of the stands is characterized by a tall-shrub stratum of *Juniperus communis* 3 feet or more in height, and a low-shrub stratum with *Symphoricarpos albus* as the most frequent species. Shrubs are also important components of the herb stratum. Dense mats of the prostrate, woody perennial *Arctostaphylos uva-ursi* are a common feature. However, the most characteristic shrub in the herb stratum is *Berberis repens*.

Many species of graminoids and forbs are present at high constancy and frequency in the herb stratum. Among the most important are *Oryzopsis asperifolia, Achillea millefolium, Fragaria vesca, Galium biflorum,* and the indigenous legumes *Vicia americana* and *Lathyrus ochroleucus*. It should be noted that except for *Berberis repens,* all of the important species in the HU also occur in several other HU. Because we are dealing with subdivisions of a larger entity with a common dominant attribute, that is, a forest dominated by *Pinus ponderosa*, the presence of many of the same species in several HU is not unexpected.

All of the soils described in this HU are developed from limestone parent material. They have well-developed sola with an A1/A2/B2/C horizon sequence. The average solum depth is 15.0 inches (range: 8.0 to 37.0 inches) and the reaction is neutral to basic through the entire solum, with strong effervescence with hydrochloric acid in the lower horizons.

Figure 2.—HU- 1: Pinus ponderosa / Juniperus communis / Symphoricarpos albus/Berberis repens

Figure 3.—HU- 2: Pinus ponderosa /Shepherdia canadensis / Symphoricarpos albus / Arctostaphylos uva-ursi

HU-2: *Pinus ponderosa/Shepherdia canadensis/Symphoricarpos albus/Arctostaphylos uva-ursi* **(fig. 3).**

HU-2 is present in the same general geographic region of the Black Hills as HU-1 (map 1), but at lower elevations (mean: 5,660 feet; range: 5,575 to 6,000 feet) and on noncalcareous geologic material. Annual precipitation for all stands is between 20 and 22 inches.

Constancy and frequency of the two smallest size classes of *Pinus ponderosa* are slightly greater than in HU-1. *Picea glauca* did not occur in any of the nine sample stands included in HU-2, but *Populus tremuloides* and *Betula papyrifera* are occasional members of the overstory canopy. *Betula papyrifera* is usually most abundant on and around outcrops of vertically oriented rock, a common feature of the HU-2 landscape.

Shepherdia canadensis is the most frequent member of the tall-shrub stratum, but it is present at relatively low constancy and frequency. *Juniperus communis* is much less frequent than in HU-1. The most important low shrubs are *Symphoricarpos albus, Rosa fendleri,* and *Amelanchier alnifolia. Arctostaphylos uva-ursi* is the shrub dominant in the herb stratum. *Berberis repens* is completely absent.

The constancy and both mean and maximum frequencies of graminoids and forbs are lower in HU-2 than in HU-1. *Danthonia intermedia* and *Agropyron griffithsi* are the most common graminoids. *Oryzopsis asperifolia* has relatively high constancy, but low frequency. *Achillea millefolium, Apocynum androsaemifolium, Antennaria neglecta,* and *Campanula rotundifolia* are high-constancy forb species. *Thermopsis rhombifolia,* present at high frequency in four of the nine stands included in the HU, is rare elsewhere in the ponderosa pine forest.

Soils in HU-2 are developed from either micaceous schists or metamorphosed rocks which are high in iron. All but one of the nine profiles described have the A1/A2/B2/C horizon sequence. The exception is located on a steep talus slope covered by an overlay of colluvium, and has an A1/C/R sequence. Soil reaction is acidic throughout the sola (mean: pH 5.7; range pH 5.1 to 6.1). The average depth to the C horizon is 15.2 inches (range: 4 to 27 inches).

HU-3: *Pinus ponderosa/Potentilla fruticosa/Symphorocarpos albus/Fragaria vesca* **(fig. 4).**

HU-3 is represented by a single stand on the north side of an exposed limestone ridge at an elevation of 6,895 feet, the highest stand sampled.

The overstory is a stand of *Pinus ponderosa* predominantly in the 4 to 8 d.b.h. class. No other species of trees are present.

The understory is characterized by a well-developed tall-shrub stratum, with *Potentilla fruticosa* as the most frequent species. This is the only HU in the ponderosa pine forest where *Potentilla fruticosa* is present at more than 8 percent frequency. In the Black Hills, it usually grows on the ecotone between mountain grasslands and ponderosa pine-white spruce *(Picea glauca)* forest on the limestone plateau. It appears to be confined to soils derived from calcareous parent materials. *Shepherdia canadensis* and *Juniperus communis* are both present at high frequency in the tall-shrub stratum. The low-shrub stratum is dominated by *Symphoricarpos albus* with *Rosa fendleri* as a species of secondary importance.

The herb stratum is poorly developed. Both *Arctostaphylos uva-ursi* and *Berberis repens* are absent. Only five species of graminoids and forbs exceed 20 percent frequency, and only 13 herb species are present. Of these, *Fragaria vesca* is the most frequent.

The solum is stony throughout with a weakly developed, clayey surface (A1) horizon about 9 inches thick. Below 9 inches the soil is approximately 80 percent limestone rock with a range in pH of 7.7 to 8.1.

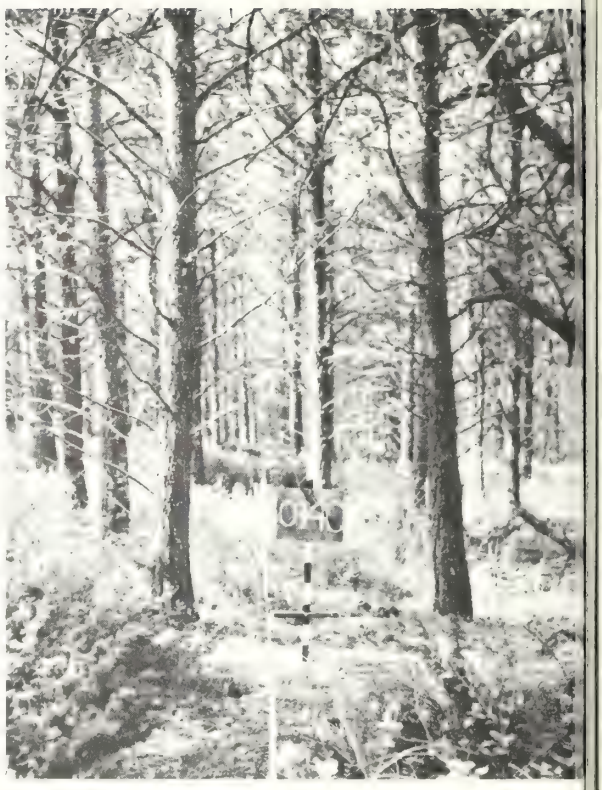


Figure 4.—HU- 3: Pinus ponderosa / Potent fruticosa / Symphoricarpos bus/Fragaria vesca

HU-4: *Pinus ponderosa/Symphoricarpos occidentalis/Rosa fendleri/Poa pratensis* **(fig. 5).**

HU-4 occupies the ecotone between dense ponderosa pine forest and adjacent meadows dominated by *Poa pratensis*. It is present at elevations averaging 5,900 feet (range: 5,100 to 6,450 feet) on a variety of geologic formations in the central region of the Black Hills. Average annual precipitation for all stands is 20 inches or more.

The *Pinus ponderosa* overstory is open, and the trees occur at much lower constancy and frequency than in any of the previously described HU.

The major species in the tall-shrub stratum is *Symphoricarpos occidentalis*. This species is indigenous to meadows at low to modera high elevations in the Black Hills, and is c mon on the prairies to the east. It does appear to be well adapted to calcareous s since it is absent from the meadows on limestone plateau.

The low-shrub stratum has *Rosa fend* and *Rosa suffulata* as the most important c ponents. Since these two species were diffic to identify on the basis of vegetative charac istics they have been combined in table 2 un *Rosa fendleri*.

Poa pratensis is by far the most import species in the herb stratum; all other graminc are present at much lower constancy and quency. The presence of *Stipa viridula* a

Figure 5.—HU- 4: Pinus ponderosa / Symphoricarpos occidentalis / Rosa fendleri/Poa pratensis

Carex heliophila in two-thirds of the stands sampled indicates the grassland affinities of the herb stratum. The relationship to adjacent grasslands is supported by the presence of such forbs as *Solidago nemoralis, Potentilla hippiana,* and *Iris missouriensis,* all of which are common meadow species in the Black Hills.

The soils in HU-4 are much deeper than in any of the previously described HU. Average depth of the solum is 23.0 inches (range: 17.0 to 34.0 inches). All horizons are dark colored and high in organic material. All but one of the described profiles have an A1/A2/B2/C horizon sequence. The A2 horizon is missing from the exception. B2 horizons are clayey with strong, angular blocky structure; soil drainage appears to be restricted by this horizon. Average soil reaction in the B2 horizon is pH 6.4.

HU-5: *Pinus ponderosa/Symphoricarpos albus/Arctostaphylos uva-ursi* **(fig. 6).**

Twenty-five stands are classified in HU-5 which is the most widely distributed unit in the ponderosa pine forest (map 4). It occurs over a large range in elevation in the northeastern, central, and southern Black Hills. The mean elevation of the 25 stands is 5,000 feet (range: 3,725 to 6,100 feet). All but three stands are on noncalcareous geologic material—mainly the micaceous schists of the central region. Those on calcareous material are located along the eastern edge of the limestone plateau at elevations between 4,000 and 5,000 feet. A majority of the stands in this HU receive less than 22 inches average annual precipitation, and in several, precipitation is below 20 inches a year.

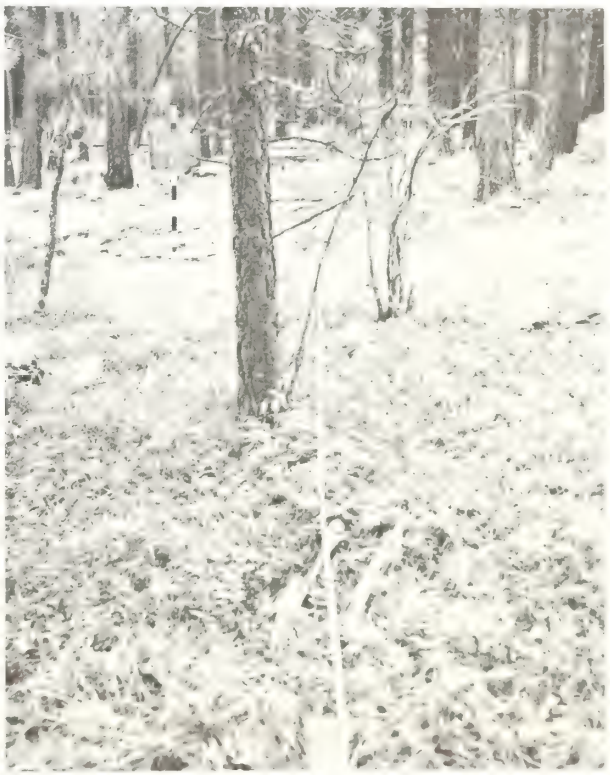


Figure 6.—HU- 5: Pinus ponderosa/Symphoricarpos albus/Arctostaphylos uva-ursi

Pinus ponderosa trees in the < 4-inch and 4- to 8-inch d.b.h. classes are very common, and several stands have such a dense overstory of small d.b.h. trees that the understory is only minimally developed. These dense stands of *Pinus ponderosa* occur only in HU-5. The causes of their origin have not been determined, but interruption of the more or less cyclic pattern of forest fires which occurred previous to settlement of the Black Hills may be an important factor in their development. Seedlings of *Pinus ponderosa* reach their greatest constancy and frequency in this HU. *Populus tremuloides, Betula papyrifera,* and *Quercus macrocarpa* are occasional members of the forest overstory.

The understory is sparsely developed with a greater incidence of bare ground and litter, and a tall-shrub stratum is absent. *Juniperus communis* and *Shepherdia canadensis* are present in some stands, but do not exceed 3 feet in height and are widely scattered. *Symphoricarpos albus* forms an open low-shrub stratum, but its mean frequency is greatly reduced from that of the previously described HU. Mats of *Arctostaphylos uva-ursi* are a common feature of the herb stratum, although it too is slightly reduced in constancy and frequency when compared to the more mesic HU previously described.

Danthonia intermedia and *Carex concinna* are the most frequent graminoids. *Achillea millefolium* is again the leading forb species. There is a distinct reduction in the constancy and frequency of all the forb species, however, which reflects the more xeric environmental conditions generally present.

Average solum depth is 14.8 inches (range: 6.0 to 30.0 inches). Upper soil horizons are quite rocky and exposed, and vertically oriented rock outcrops are a common feature of the landscape. The subsoil is generally acidic except on limestone, where it may reach pH 8.5. The horizon sequences are either A1/A2/B2/C or A1/B2/C. An A2 horizon is present in 17 of the 25 profiles. All but one of the soils without an A2 horizon have B2 horizons; the exception has an A1/AC/C sequence.

HU-6: *Pinus ponderosa-Quercus macrocarpa Prunus virginiana/Symphoricarpos a bus/Berberis repens* **(fig. 7).**

HU-6 is represented by four stands, al located along the northern edge of the Blac Hills at elevations between 3,850 and 4,550 fee All of the stands are on calcareous geologi material and lie between the 20- and 22-inc isohyets.

Small *Quercus macrocarpa* are the mos frequent overstory species, but the averag height of these trees is less than that of th intermixed *Pinus ponderosa*. Both species hav been logged in the past. Many large-diamete stumps of *Quercus macrocarpa* are presen and many of the small trees have sproute from old root crowns.

The tall-shrub stratum is well developed *Prunus virginiana, Quercus macrocarpa,* an *Amelanchier alnifolia* all occur at high constanc and frequency, and may exceed 6 feet in heigh

Figure 7.—HU- 6: Pinus ponderosa - Quercu macrocarpa / Prunus virgini ana / Symphoricarpos albus, Berberis repens

ıe first and last of these tall shrubs are esent over much of the ponderosa pine forest, t are usually not over 1.5 feet tall. *Ostrya rginiana* forms a tall-shrub stratum over 10 et high in three of the four stands. *Quercus acrocarpa* and *Ostrya virginiana* are sympatric ong much of the northern edge of the Black lls. The low shrub stratum is dominated by *mphoricarpos albus* and *Spiraea lucida*. *Berris repens* occurs at high frequency in the erb stratum and *Toxicodendron radicans* is esent at low frequency in all stands.

Many graminoids and forbs are present at gh frequency in the herb stratum in spite of e dense shrub strata. Many of these are ecies also found throughout the ponderosa ne forest, but two species, *Maianthemum nadense* and *Sanicula marilandica*, are rare cept in this HU.

The soils in HU-6 are deeper than in most the other HU of the ponderosa pine forest. ıe average solum thickness is 24.3 inches with range of 14.0 to 29.0 inches. All four profiles e well developed with the A1/A2/B2/C horizon quence and have neutral to basic reaction. ıe O1 horizon (litter) is thicker than in any her HU because of the accumulation of leaves om *Quercus macrocarpa* and the many ciduous shrubs.

Figure 8.—HU- 7: Pinus ponderosa - Quercus macrocarpa / Prunus virginiana / Symphoricarpos albus / Schizachne purpurascens - Carex foenea

U-7: *Pinus ponderosa-Quercus macrocarpa/ Prunus virginiana/Symphoricarpos albus/Schizachne purpurascens-Carex foenea* **(fig. 8).**

HU-7 is represented by a single stand on e eastern edge of the central Black Hills at elevation of 4,300 feet. It is related to HU-6 several attributes, but differs in that it curs on a very acidic soil, has a greater equency of large-diameter *Quercus macrorpa* in the overstory, and a herb stratum minated by graminoids.

Quercus macrocarpa is codominant in the erstory with *Pinus ponderosa*. A few *Quers macrocarpa* trees larger than 12 inches o.h. are scattered through the stand. Many rge-diameter stumps suggest that *Quercus acrocarpa* may have been the dominant species ior to logging. *Pinus ponderosa* in the 4- to nch d.b.h. class is presently the most frequent erstory species.

Prunus virginiana is the most frequent species in the tall-shrub stratum, and *Symphoricarpos albus* is the low-shrub dominant. Neither *Berberis repens* nor *Toxicodendron radicans* are present in the herb stratum. *Carex foenea* and *Schizachne purpurascens* both occur at high frequency in the herb stratum. *Schizachne purpurascens* is rare elsewhere in the ponderosa pine forest. The forb *Smilacina stellata* is also present with moderate frequency and gives the herb stratum a distinctive appearance.

The solum has an A1/A2/B2/B3 horizon sequence, and is more than 36 inches deep. The B2 horizon is very acidic (pH 4.5) which may account for the absence of *Berberis repens*. A litter horizon (O1) and a well-defined humus horizon (O2) are present.

HU-8: *Pinus ponderosa/Prunus virginiana/ Amelanchier alnifolia/Galium biflorum* **(fig. 9).**

HU-8 is represented by one stand at the base of a steep limestone cliff along one of the major streams (Little Spearfish Creek) in the northern Black Hills. This very mesic, protected, semiriparian site is between the 22- and 24-inch isohyets, although the elevation is only 5,200 feet.

The overstory is a rather open stand of small-diameter *Pinus ponderosa.* A few *Betula papyrifera* up to 15 feet tall are scattered through the stand. The tall-shrub stratum is composed of *Prunus virginiana, Shepherdia canadensis,* and *Corylus cornuta.* This is the only HU in the ponderosa pine forest where *Corylus cornuta* is present at high frequency. *Cornus stolonifera,* present at low frequency, indicates the mesic nature of this HU since in the Black Hills it grows only along streams.

The low-shrub stratum is well developed with *Amelanchier alnifolia* present at high frequency. *Symphoricarpos albus, Spiraea lucida,* and *Rosa fendleri* occur at moderately high frequency. *Berberis repens* and *Arctostaphylos uva-ursi* are prominent but do not dominate the herb stratum. *Poa pratensis* is the only graminoid to exceed 20 percent frequency. Several forb species are present at frequencies exceeding 20 percent. *Galium biflorum* is the herb stratum dominant. *Monarda fistulosa* is also abundant.

The soil is developed from limestone colluvium. The solum is 20.0 inches deep, rocky throughout, and has a basic reaction. An O1 horizon 1-1/2 inches thick and a 1/2-inch-thick O2 horizon are present. The horizon sequence is A1/A2/B2/R.

Figure 9.—HU- 8: Pinus ponderosa / Prunus virginiana / Amelanchier alnifolia / Galium biflorum

Figure 10.—HU- 9:
Pinus ponderosa / Poa pratensis - Danthonia intermedia

HU-9: *Pinus ponderosa /Poa pratensis-Danthonia intermedia* **(fig. 10).**

HU-9 is represented by seven stands, five in the southern Black Hills (map 4). The other two are located on exposed sites in old forest fire burns. The average elevation of all stands is 5,250 feet (range: 4,950 to 5,500 feet). Most lie between the 18- and 20-inch isohyets. Five of the stands occur on granitic material, one on calcareous material, and one on micaceous shale.

Pinus ponderosa is the only overstory species. The overstory canopy is open, and all d.b.h. classes are present at low frequency. Many of the trees are short with heavy limbs.

No shrub species are present at more than 67 percent constancy, and the general appearance of the HU is that of an open pine stand with a grassy understory. *Poa pratensis* is by far the most frequent species in the herb stratum; in one stand it occurred at 99 percent frequency. *Danthonia intermedia* and *Koeleria cristata* are also present in all stands, but always at lower frequencies than *Poa pratensis*. *Achillea millefolium* is the only forb species with 100 percent constancy. Most of the forbs present are species common to moderately moist grasslands at moderate elevations in the Black Hills.

Sola average 12.0 inches in thickness. The B2 horizon is absent from five of the seven soil profiles, and the general horizon sequence is A1/AC/C/R. One of the two soils with a B2 horizon is located on old forest fire burn in the central Black Hills. The other is in a moist draw on calcareous parent material. B2 horizons appear to develop more readily on calcareous than on noncalcareous parent materials.

HU-10: *Pinus ponderosa-Juniperus scopulorum/Cercocarpus montanus/Symphoricarpos albus/Andropogon scoparius* **(fig. 11).**

HU-10 is represented by three stands in the southwestern Black Hills (map 4). The mean elevation of the stands is 5,225 feet (range: 5,000 to 5,475 feet). Mean annual precipitation is 18 to 20 inches.

The overstory is characterized by an open stand of *Pinus ponderosa* with scattered *Juniperus scopulorum.*

The tall-shrub stratum is a dense stand of *Cercocarpus montanus.* Individual plants exceed 10 feet in height and grow so closely together that movement through the stand is very difficult. *Cercocarpus montanus* is very localized in the Black Hills. It grows only on the limestone formations along the southwestern, southern, and southeastern periphery of the Black Hills. In spite of the limited number of representative stands, this HU is a distinct unit, easily recognizable in the field. The three stands have a minimum similarity of K>70. HU-10 resembles the mountain brush type found at low to moderate elevations throughout much of the central Rocky Mountain region.

A number of other shrub species which are uncommon elsewhere in the ponderosa pine forest of the Black Hills are found in this HU. Among these are *Rhus trilobata, Ribes inerme,* and *Yucca glauca. Symphoricarpos albus* is frequent in the low-shrub stratum.

The major species in the herb stratum are graminoids and forbs with prairie affinities. *Andropogon scoparius, Agropyron smithii, Bouteloua curtipendula,* and *Koeleria cristata* are the more important graminoids. *Artemisia ludoviciana, Phlox hoodii, Anemone patens, Zygadenus elegans,* and *Hymenoxys acaulis* are present in all stands. The presence of *Musineon divaricatum, Grindelia squarrosa,* and *Leucocrinum montanum,* even with less than 100 percent constancy, is a further indication of the prairie affinities of the herb stratum.

The soil parent material under all stands is limestone. The horizon sequence is A1/AC/C/R, and soil texture is a stony or gravelly loam throughout the solum. Solum depths range from 7 to 31 inches, with strong hydrochloric acid effervescence in all horizons.

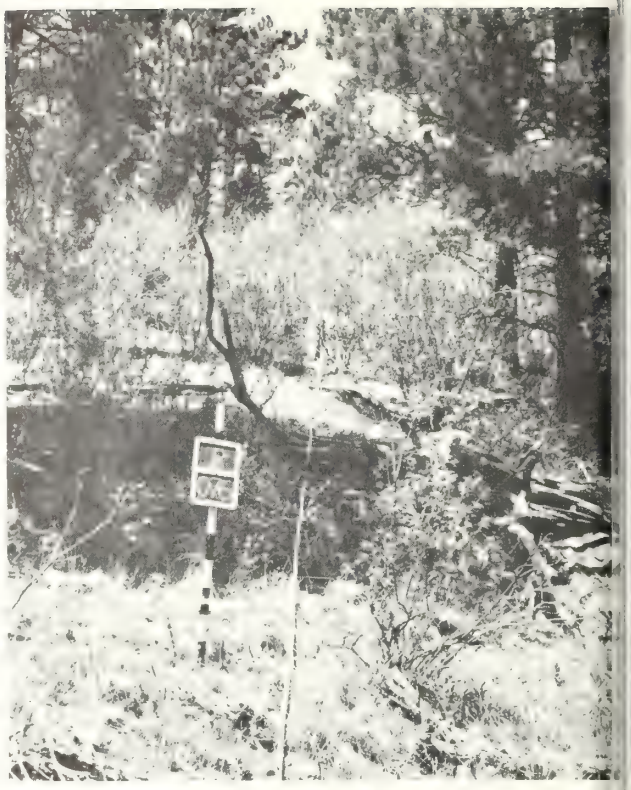


Figure 11.—HU-10: Pinus ponderosa - Juniperus scopulorum / Cercocarpus montanus / Symphoricarpos albus / Andropogon scoparius

Figure 12.—HU-11: Pinus ponderosa / Andropogon scoparius

HU-11: *Pinus ponderosa/Andropogon scoparius* (fig. 12).

HU-11 is confined to the southwestern part of the Black Hills, a relatively low and dry region with rolling topography. The ponderosa pine forest is interspersed among extensive dry prairies, and generally occurs along watercourses and the mesic aspects of hills and canyons. The average elevation of the nine stands representing this HU is 5,165 feet (range: 4,825 to 5,475 feet). Most of the stands are between the 18- and 20-inch isohytes, with several stands having less than 18 inches mean annual precipitation. The limestone plateau is very extensive in this part of the Black Hills, and all of the stands are located on this geologic formation.

The *Pinus ponderosa* overstory is relatively dense. Trees greater than 4 inches d.b.h. are frequent, as are seedlings. Larger *Pinus ponderosa* trees are usually limby and flat-topped. *Juniperus scopulorum* is sometimes present as a subordinate tree. Only two species of low-shrubs, *Rosa fendleri* and *Symphoricarpos albus,* are present. Neither exceeds 67 percent constancy and they occur only at low frequency and are rarely more than 1 foot in height.

The herb stratum is related to the surrounding prairie. *Andropogon scoparius* is the most frequent species and the only one with 100 percent constancy. *Koeleria cristata* is present in all but one stand, but never exceeds 10 percent frequency. The presence of *Leucocrinum montanum* and *Phlox alyssifolia* in many stands indicates the prairie affinities of the herb stratum.

Sola are relatively deep (mean: 19.7 inches; range: 10.0 to 26.0 inches) and have an A1/B2/C/R horizon sequence. Soil reaction is neutral to basic (pH 7.2 to 8.0) in the subsurface horizons and only slightly acid in the surface horizons. The surface horizons are relatively deep and dark colored from the presence of fibrous roots of graminoid species.

HU-12: *Pinus ponderosa/Prunus virginiana/ Andropogon scoparius* **(fig. 13).**

HU-12 is represented by nine stands on the periphery of the Black Hills at elevations below 4,700 feet (mean: 4,265 feet; range: 3,925 to 4,675 feet). The northern and extreme southern stands are on calcareous geologic material, while those in the east-central foothills are underlain by either granitic or metamorphosed formations. Mean annual precipitation for all stands is between 18 and 20 inches.

The overstory is open and trees are short with large limbs. Seedlings of *Pinus ponderosa* are relatively common. Small *Quercus macrocarpa* are present in several stands, and the general appearance of the overstory is that of an impoverished HU-6. *Juniperus scopulorum* was present in one stand.

The understory is also quite open and without a tall-shrub stratum. The low-shrub stratum has *Prunus virginiana* as the most frequent species; plants are almost always under 2 feet high when mature. *Rosa fendleri* is the second most constant shrub. Both *Symphoricarpos occidentalis* and *S. albus* are present, but at low constancy, although occasionally at high frequency. *Amorpha canescens* is also common in the low shrub stratum.

Andropogon scoparius is the most frequent species in the herb stratum. *Lupinus parviflorus* and *Artemisia ludoviciana* are also common constituents.

Soil depths are variable. Two of the stands have soils with shallow sola (1.5 and 12.0 inches) and an A1/C/R horizon sequence. The other seven stands have deep sola (mean: 28.1 inches; range: 23.0 to 41.0 inches) with an A1/B2/C/R sequence. The subsoil reaction on the soils developed from limestone is as high as pH 9.0. On noncalcareous soils the subsoil is acidic (pH 6.0 to 6.6).

Figure 13.—HU-12: Pinus ponderosa / Prunus virginiana /Andropogon scoparius

U-13: *Pinus ponderosa/Andropogon scoparius-Bouteloua gracilis* **(fig. 14).**

The single stand representing HU-13 is cated in the extreme southeastern Black Hills an elevation of 4,675 feet. This is the most eric part of the region, with an annual pre-pitation between 16 and 18 inches.

Only scattered *Pinus ponderosa* are present this area. No tree size *Pinus ponderosa* e present on the sample plot and the general pearance of the site is that of an *Andro-gon scoparius* grassland. A few *Pinus pon-rosa* seedlings are present which indicates e area can support the species.

igure 14.—HU-13: Pinus ponderosa / Andropogon scoparius-Bouteloua gracilis

The only shrub species present is *Artemisia frigida. Andropogon scoparius, Bouteloua gracilis,* and *B. curtipendula* are the most frequent graminoids. *Stipa comata* and *Andropogon gerardii* are present at low frequency. Several of the forb species occur only in this HU. Among these are *Polygala alba, Echinacea angustifolia, Chrysopsis villosa, Paronychia depressa,* and *Hackelia virginiana.* All are prairie species.

The soil in this HU is derived from limestone and has an A1/AC/C profile. Depth to the top of the C horizon is 22 inches. The A1 horizon is dark colored and high in grass roots. Soil reaction is pH 7.4 or greater throughout the solum.

DISCUSSION

The purpose of habitat classification for wildlife management is to separate a large, heterogeneous habitat into more homogeneous units which are enough alike to be administered, manipulated, or evaluated in groups. Previously, habitats have been grouped almost entirely by subjective methods. While this may be satisfactory for extensive management, or where distinctly different kinds of habitats exist sympatrically, more objective classification methods, particularly those based on quantitative evaluation of actual features or attributes of the area under consideration, are needed for intensive management. This is particularly true for habitats such as the ponderosa pine forest of the Black Hills which cover extensive areas, or have a relatively homogeneous feature such as a closed canopy tree overstory which makes the understory or other habitat variations difficult to distinguish.

The application of computers to the solution of classification problems in plant taxonomy and ecology has received a great deal of attention in recent years. Techniques are available to make ordered and logical arrangements of heterogeneous entities. The method used in this study, cluster analysis, is only one of the many available. It may be defined as an agglomerative (combination of individual entities into a whole) mathematical procedure which groups together entities with the greatest number of shared attributes.

Although HU may be designated at minimum levels of similarity higher than $K \geq 60$, both

the total number of HU and the percentage of HU containing three or less stands increase greatly (table 3).

The number of HU approximately doubles for each 5 percent increase in K, while the percentage of HU containing three or less stands increases from 39 percent at $K \geq 60$, to 57 percent at $K \geq 65$, and to 91 percent at $K \geq 70$. Increasing the minimum level of similarity higher than $K \geq 60$ apparently defeats the purpose of classification, which is to obtain groups of relatively similar stands.

At $K \geq 84$, all HU consist of a single stand, and an ordination of stands is obtained. For some purposes, ordination may be a useful technique of analysis, especially where strong environmental gradients are present. It should be noted that there is an element of ordination in the arrangement of the dendrogram (fig. 1): there is a general decrease in precipitation, elevation, etc., from top to bottom. However, there are also abrupt changes in other environmental features of the Black Hills such as geological formation, and these are reflected in abrupt changes in species composition and other attributes. Therefore, classification of stands appears to be a more appropriate technique of analysis.

In assessing the validity of the classification of the ponderosa pine forest ecosystem, several points must be emphasized. First, as with a classification, only the things being classified in this instance, the sample stands—are re in the sense that they actually occur in natu Each stand has a set of measurable (or least recordable) attributes of vegetation, so and site which characterize it. These attribut are the result of a sequence of environmen events, the majority of which are usually u known. Furthermore, the combination of att butes which characterize a stand exist only the specific time at which they were record due to succession, disturbance, and chan Because of their dynamic nature, no two stan can be expected to be exactly alike.

Second, any classification unit, such as HU, is an abstraction based on the modal cha acteristics of a number of sample stands whi usually are widely separated geographicall The range of attribute characteristics of a u depends on the attribute variability of t included stands, and the level of homogenei at which it has been defined. This level homogeneity, in turn, depends upon the purpo for which the classification has been mad For some purposes, very high levels homogeneity may be desirable; for other pu poses, lower levels may be adequate, or ev necessary. Because of the interdependence homogeneity and purpose, there does not

Table 3.--Number of habitat units (HU) with one, two, three, or more included stands for levels of similarity of $K \geq 60$, $K \geq 65$, and $K \geq 70$

Number of included stands	HU at $K \geq 60$		HU at $K \geq 65$		HU at $K \geq 70$	
	Number	*Percent*	*Number*	*Percent*	*Number*	*Percent*
1	4	31	5	19	29	57
2	--	--	5	19	13	26
3	1	8	5	19	4	8
4+	8	61	11	43	5	9
Total	13	100	26	100	51	100

ear to be an intrinsic level of homogeneity which classification units must, or should, e defined.

Third, synecological classification units such HU are best defined on a multi-attribute asis, although they often may be recognized nd described by relatively few important or ndicator" attributes. A stand which is said "belong" to a given HU need not possess l of the attributes which define the HU. urthermore, since the HU are defined on this ulti-attribute basis, the effect of the presence absence of a single attribute is minimal. his minimal effect is enhanced, of course, hen attributes are unweighted and/or andardized.

Finally, there is the question: What conitutes a "good" classification? For syneological purposes, units in a good classification ow close relationship with what occurs in ature. The classification must provide a logical paration of the landscape into units, examples tands) of which may be easily recognized in e field, and which may be related to the vironmental regime.

The 13 HU defined at K $\geq$60 appear to conitute a realistic classification of the ponderosa ne forest of the Black Hills. There is a asonable number of units, examples (stands) which can be easily recognized in the field the presence and prevalence of certain attriutes, particularly plant species.

The major (multistand) HU show a good lationship with environmental features of the lack Hills, especially geological formation and recipitation regime, neither of which were rectly used in the calculation of the similarity atrix. The general regions of the Black Hills here a given HU can be expected to preominate can be mapped (map 4).

The major multistand HU, HU-1 (*Pinus onderosa/Juniperus communis/Symphoricarpos albus/Berberis repens)* and HU-5 *(Pinus onderosa/Symphoricarpos albus/Arctostaphyos uva-ursi)* are the most extensive subdivisions the ponderosa pine forest. In general, they ccupy separate geographic regions of the Black ills and, although many plant species are ommon to both, there are distinct differences both overstory and understory characterics and in environment which make them stinguishable in the field.

HU-2 *(Pinus ponderosa/Shepherdia canaensis/Symphoricarpos albus/Arctostaphylos va-ursi)* is in many attributes intermediate etween HU-1 and HU-5. It might be described a mesic phase of HU-5. It also has close relationship to HU-1; the major differentiating attributes are the absence of *Berberis repens* and the occurrence on noncalcareous geological materials. These, of course, are interrelated, since *Berberis repens* is apparently confined to calcareous soils in the Black Hills. Although it occurs in the same general geographic area and at similar elevations, HU-4 *(Pinus ponderosa/Symphoricarpos occidentalis/Rosa fendleri/Poa pratensis)* is easily distinguished from the above three HU by the dominance of *Symphoricarpos occidentalis* in the tall-shrub stratum and the very open overstory of *Pinus ponderosa.*

Except for HU-10 *(Pinus ponderosa-Juniperus scopulorum/Cercocarpus montanus/Symphoricarpos albus/Andropogon scoparius)* which is distinct due to the dominance of *Cercocarpus montanus* in the understory, the remaining multistand HU are less easy to define. In general, they represent the transition zone between ponderosa pine forest and the Northern Great Plains. HU-9 *(Pinus ponderosa/Poa pratensis-Danthonia intermedia)* occupies the most mesic sites in this more xeric region of the Black Hills. HU-12 *(Pinus ponderosa/Prunus virginiana/Andropogon scoparius)* occurs on exposed locations in the more mesic northern and eastern foothills, and shows relationships in a few attributes to HU-6 *(Pinus ponderosa-Quercus macrocarpa/Prunus virginiana/Symphoricarpos albus/Berberis repens)* and HU-7 *(Pinus ponderosa-Quercus macrocarpa/Prunus virginiana/Symphoricarpos albus/Schizachne purpurascens-Carex foenea)* particularly in the presence of *Quercus macrocarpus* at low frequency in some of the stands. HU-11 *(Pinus ponderosa/Andropogon scoparius)* occupies the most xeric sites with a *Pinus ponderosa* overstory. The general appearance of most of the stands is that of a ponderosa pine savanna.

The four single-stand HU defined at K $\geq$60 are distinct in many attributes. Two of them, HU-3 *(Pinus ponderosa/Potentilla fruticosa/Symphoricarpos albus/Fragaria vesca)* and HU-8 *(Pinus ponderosa/Prunus virginiana/Amelanchier alnifolia/Galium biflorum)* occur in mesic environments, the former in a high elevation, high precipitation zone and the latter on a shaded river bench in a deep canyon. The third, HU-7 *(Pinus ponderosa-Quercus macrocarpus/Prunus virginiana/Schizachne purpurascens)* has close similarities with HU-6 *(Pinus ponderosa/Quercus macrocarpus/Prunus virginiana/Berberis repens)* and at K $\geq$59 these would be combined. There are distinct differences in understory species composition and soil attributes, however, which distinguish HU-6

from HU-7. The final single-stand unit, HU-13 *(Pinus ponderosa/Andropogon scoparius-Bouteloua gracilis)* is more representative of the Northern Great Plains than the ponderosa pine forest. It was the final stand to be incorporated into the cluster analysis, which emphasizes its lack of similarity with the other 99 stands.

The disturbed condition of all 100 stands makes any discussion of the successional status of the HU rather tentative. There is a degree of floristic similarity between all stands, and if the HU had been defined only on floristics, this possibility of successional stages might be difficult to resolve. However, soil-site attributes were also utilized in the classification of the stands into HU, and these less easily altered attributes also show a considerable degree of within-HU similarity, it is believed the HU represent distinct climax types (in the sense of Tansley 1949, not Clements 1936), although in a disclimax stage mainly due to man-caused disturbances.

As with any classification scheme, the classification of the ponderosa pine forest presented here should and will be modified as knowledge of the subject increases. However, in its present form it provides a framework for studies of practices to improve forage production, utilization, nutrition, and habitat carrying capacity. As such, it can be a useful tool for deer habitat management in the Black Hills.

HABITAT EVALUATION

Long-term data on pellet group densiti collected by the South Dakota Game, Fish, ar Parks Department on segments of the 1,00 foot transect within the 60 x 100-foot macropl were used to evaluate the degree of deer use the HU defined at K ≥60. No attempt has bee made to convert pellet group densities to anim numbers; they were used directly, and only an index of the comparative use of the habit units by deer as suggested by Riney (1957

Differences in mean pellet group densiti (table 4) between HU were analyzed by anal sis of variance—one-way classification, wit unequal sample sizes (Li 1957). The resul of this analysis indicated there was a significa difference (p = .05) in the mean pellet grou densities.

To test the significance of differences b tween means, the multiple range test (Dunca 1955) was applied. The results of this tes are shown in table 4 by the underscored line

The following explanation of the variab deer use of the HU is based on studies by th South Dakota Game, Fish, and Parks Depar ment, the Wildlife Habitat Research Unit the Rocky Mountain Forest and Range Exper ment Station, and personal experience of th author in the Black Hills. In assessing th validity of the explanation, some points shou be kept in mind. First, although pondero pine forest is the most widespread habit

Table 4.--Mean pellet group densities[1] (1960-68) for the 13 Habitat Units (HU) defined at K≥60

Item	Habitat Unit												
	6	4	7	8	10	2	9	1	12	5	11	3	
Number of stands	4	6	1	1	3	9	7	24	9	25	9	1	
Mean pellet group density	10.0	9.7	6.6	5.7	4.9	4.8	4.4	4.2	4.0	3.0	2.6	0.6	0
	NSD[2] a = .05												
			NSD a = .05										
									NSD a = .05				

[1] Density recorded on a 6- by 100-foot plot.
[2] Nonsignificant difference.

available to deer in the Black Hills, other habitats such as quaking aspen *(Populus tremuloides)* woodland, old forest fire burns, and mountain meadows, not included in this classification are also important deer habitats. Second, the juxtaposition of the ponderosa pine forest with these other habitats influences use by deer. Third, the white-tailed deer in the Black Hills are noticeably more migratory than is usually expected for this species, and tend to move considerable distances and occupy distinct winter, spring, and summer-fall ranges.

HU-6, HU-4, and HU-7 had the highest mean pellet group densities (10.0 to 6.6). HU-6 occurs only in the northern foothills of the Black Hills, and is an area where deer concentrate during the winter. Low elevation and relatively little snow, plus the presence of several palatable species of browse, combine to make this HU attractive to deer during the winter. HU-4 represents important spring deer range in the Black Hills. During April and May this HU and adjacent meadows are favored feeding areas for deer. Their diet during this period consists mostly of *Poa pratensis* [4] which is the dominant herb species in HU-4. HU-7 is also a low-elevation winter range, and is similar to HU-6 in many attributes.

The six HU with moderate pellet group densities (5.7 to 4.0) range from mesic, high-elevation forest (1, 2, 8) to xeric, low-elevation forested shrubland (9, 10) and forested grassland (12). Three (8, 10, 12) are winter range in various parts of the Black Hills, one (9) is spring range, and the remaining two (10, 2) are important summer-fall deer range.

Of the four remaining HU, with low pellet group densities (3.0 to 0.1), HU-5 is the most widely distributed, and, because of its location at moderate elevations, is probably both year-long and transition range. While it has only relatively low deer use, because of its wide distribution it is still important deer habitat. HU-11 is located mainly in the southwestern Black Hills at low elevation and is winter range. The remaining two HU (3, 13) represent extremes in the ponderosa pine forest, and are each represented by a single stand. The former is located at almost the maximum elevation possible in the Black Hills, and has an understory dominated by a dense stand of the unpalatable shrub, *Potentilla fruticosa;* the latter is an open grassland in the most xeric portion of the Black Hills and provides little in the way of forage or cover for deer.

[4] *Dietz, Donald R. Personal communication.*

SUMMARY

Cluster analysis of a similarity matrix derived from the ecological attributes (vegetation, soil, and site characteristics) of 100 stands located throughout the ponderosa pine forest of the Black Hills produced a classification of the forest into 13 Habitat Units (HU) with a minimum internal similarity of 60 percent.

The coefficient of similarity, $K = 2c/a + b$, was used to construct the initial matrix, and the weighted-pair group method of cluster analysis was used to separate this matrix into the Habitat Units (groups of similar stands).

The indicator species of the overstory, shrub, and herb strata and the number of stands included in each HU are:

HU-1: *Pinus ponderosa/Juniperus communis/Symphoricarpos albus/Berberis repens* (24 stands)

HU-2: *Pinus ponderosa/Shepherdia canadensis/Symphoricarpos albus/Arctostaphylos uva-ursi* (9 stands)

HU-3: *Pinus ponderosa/Potentilla fruticosa/Symphoricarpos albus/Fragaria vesca* (1 stand)

HU-4: *Pinus ponderosa/Symphoricarpos occidentalis/Rosa fendleri/Poa pratensis* (6 stands)

HU-5: *Pinus ponderosa/Symphoricarpos albus/Arctostaphylos uva-ursi* (25 stands)

HU-6: *Pinus ponderosa-Quercus macrocarpa/Prunus virginiana/Symphoricarpos albus/Berberis repens* (4 stands)

HU-7: *Pinus ponderosa-Quercus macrocarpa, Prunus virginiana/Symphoricarpos albus/Schizachne purpurascens-Carex foenea* (1 stand)

HU-8: *Pinus ponderosa/Prunus virginiana/Amelanchier alnifolia/Galium biflorum* (1 stand)

HU-9: *Pinus ponderosa/Poa pratensis-Danthonia intermedia* (7 stands)

HU-10: *Pinus ponderosa-Juniperus scopulorum/Cercocarpus montanus/Symphoricarpos albus/Andropogon scoparius* (3 stands)

HU-11: *Pinus ponderosa/Andropogon scoparius* (9 stands)

HU-12: *Pinus ponderosa/Prunus virginiana Andropogon scoparius* (9 stands)

HU-13: *Pinus ponderosa/Andropogon scopari us-Bouteloua gracilis* (1 stand)

Data on pellet group density collected in the sample stands over a 9-year period were analyzed to evaluate the comparative use of the different HU by deer. The results of this analysis indicated HU-6, -4, and -7 received

significantly higher deer use (mean pellet group densities 10.0 to 6.6) than the other HU; HU-8, -10, -2, -9, -1, and -12 received moderate deer use (mean pellet group densities 5.7 to 4.0) and HU-5, -11, -3, and -13 received only light deer use (mean pellet group densities 3.0 to 0.1).

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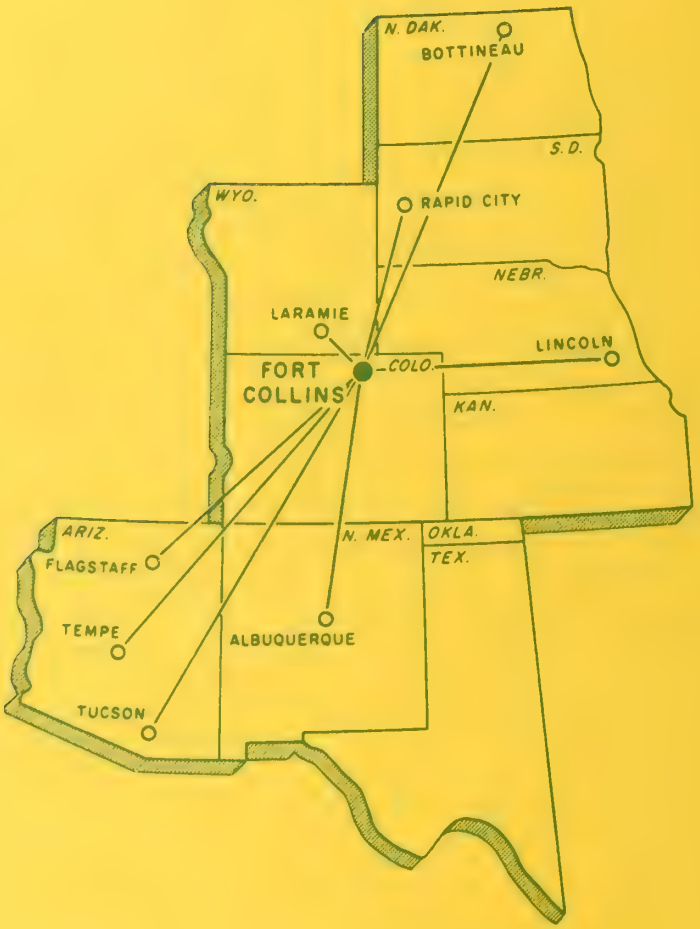
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PARTIAL CUTTING PRACTICES IN OLD-GROWTH LODGEPOLE PINE

by Robert R. Alexander

AUG 31 1972

For convenient field use, the stand descriptions, cutting practices, windfall risk situations, dwarf mistletoe rating system, and tree vigor classification in this Research Paper have been published separately in a smaller format (5-½ x 8-½ inches) as USDA Forest Service Research Paper RM-92A, "Partial Cutting Practices for Old-Growth Lodgepole Pine — A Field Guide." Copies of RM-92A are available from the Rocky Mountain Forest and Range Experiment Station, 240 West Prospect Street, Fort Collins, Colorado 80521.

Abstract

Guidelines are provided to aid the forest manager in developing partial cutting practices to maintain continuous forest cover in travel influence zones, and in areas of high recreational values or outstanding scenic beauty. These guidelines consider stand conditions, windfall risk situations, and insect and disease problems. These cutting practices may be also used in combination with small cleared openings to create the kinds of stands desirable for increased water yields, improvement of wildlife habitat, and to integrate timber production with other uses. On areas where timber production is the primary objective, clearcutting in small, dispersed units is the recommended method of harvesting trees.

Key Words: Forest cutting systems, *Pinus contorta*, stand condition, windfall risk, dwarf mistletoe, mountain pine beetle.

About the cover:
New reproduction established after a light shelterwood cutting in lodgepole pine on the Fraser Experimental Forest, Colorado.

USDA Forest Service
Research Paper RM-92

June 1972

Partial Cutting Practices for Old-Growth Lodgepole Pine

by

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[1]*Central Headquarters maintained at Fort Collins, Colorado in cooperation with Colorado State University.*

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Partial Cutting Practices for Old-Growth Lodgepole Pine

Robert R. Alexander

rom a silvicultural point of view, clearcutting is sound and practical way of bringing mature d overmature lodgepole pine (*Pinus contorta* ougl.) forests under management, especially nen timber production is a major objective. here are several reasons for clearcutting. Since ese have been thoroughly discussed by Tackle 961), they will only be highlighted here:

Lodgepole pine, a pioneer species, is shade intolerant and reproduces most satisfactorily when overstory competition is removed or drastically reduced.

Dwarf mistletoe (*Arceuthobium americanum* Nutt. ex Engelm.) — present in varying degrees in many mature to overmature stands — is best controlled by separating old and new stands.

Windfall, while variable, is always a threat to lodgepole pine forests.

The potential for future growth is limited because of the generally low vigor of mature and overmature stands, and the suppressed condition of many of the smaller trees.

rthermore, many natural stands appear to be en-aged because they developed after fires, or her catastrophic disturbances.

mber production is, however, only one of the y uses of lodgepole pine forests in the central ocky Mountains. They occupy areas that also e important for water yield, wildlife habitat, creation, and scenic beauty. Forest managers ust consider how these areas are to be handled meet the increasing demands of the public. e visual and environmental impacts of clear- tting for timber production are not always mpatible with the objectives of other key s. Described below are the kinds of stands that are desirable for increased water yields, improvement of wildlife habitat, preservation of the forest landscape, and maintenance of scenic values. What is needed are silvicultural practices that can be used alone or in combination with small cleared areas to maintain forest cover while gradually replacing the old stand with a healthy vigorous new one.

FORM, STRUCTURE, AND ARRANGEMENT OF STANDS FOR KEY USES

Guidelines to aid the forest manager in developing alternatives to clearcutting in spruce-fir forests (Alexander 1971) contain similar descriptions of the kinds of stands desirable for uses other than timber production. They are repeated here for emphasis.

Water

Snowfall is the key to water yield in lodgepole pine forests. Comparisons of cut and uncut plots (8 acres in size), on the Fraser Experimental Forest in Colorado, have shown that more snow accumulated in cutover areas than under adjacent uncut stands. Accumulations were greatest on plots that were clearcut (Wilm and Dunford 1948, Hoover and Leaf 1967). The increased snow depth is not additional snow, however, but a redistribution of snow. Wind transports the snow intercepted on the surrounding trees and deposits it in the openings. Some of the increase in water equivalent in the openings is available, however, for streamflow (Hoover and Leaf 1967).

Research and experience suggest that a round or patch-shaped opening, about five to eight times

tree height in diameter, is the most effective for trapping snow (Hoover 1969). In larger openings, wind is likely to dip down to the ground and blow the snow out of the openings. About one-third of the forest area in openings distributed over the watershed appears to be the best arrangement. These openings could either be maintained permanently or regenerated to new growth that would be periodically recut when trees reach about half the height of the surrounding trees. The remaining two-thirds of the area should be retained as continuous high forest, since the taller trees control snow deposition. Trees would be periodically harvested on an individual-tree basis or in small groups (one to two times tree height) to gradually replace the old with a new stand. Ultimately, the reserve stand would approach a broad-aged structure with the overstory canopy remaining at about the original height. An alternative would be to make a light cut distributed over the entire watershed, removing about 20 to 30 percent of the basal area on an individual-tree basis or in small groups. The objective is to open up the stand enough to develop windfirmness, and salvage low vigor and poor risk trees. Openings five to eight times tree height can then be cut on about one-third of the area. The remaining two-thirds of the area would be retained as permanent high forests, with trees periodically removed on an individual-tree basis or in small groups.

Another alternative that would integrate wa and timber production would be to harvest al the old growth on a watershed with a series cuts spread over a period of 120 to 160 ye At intervals of about 20 to 40 years, a port of the area would be harvested in small openi — four to five times tree height — distribu over the watershed. The number of openings at each interval would depend on the size of watershed and the length of rotation and cutt cycle selected. These openings would regenerated so that at the end of one rotati the watershed would contain groups of tree several age classes from reproduction to th ready for harvest. The tallest trees may somewhat shorter than the original overst but the adverse effects on snow deposit should be minimized by keeping the openi small. At the end of one rotation, the fo manager has the option of following the s procedure through the next rotation or selec about one-third of the openings to be m tained as snow-trapping areas, and conver the remaining area into a broad-aged stand periodically removing individual trees.

Wildlife

The use of lodgepole pine forests by Ro Mountain mule deer (*Odocoileus hemio hemionus* Rafinesque) is influenced by tim cutting practices. On the Fraser Experime

Natural reproduction establ in a cleared opening about 5 times tree height in lodg pine on the Fraser Experim Forest.

rest, there was more deer use and a greater undance and selection of forage species on arcut openings than under adjacent uncut nds (Wallmo 1969, Wallmo et al. 1972). enings three chains wide were used more than her wider or narrower openings. Forage oduction appears to decline about 10 years er cutting, however, as tree reproduction laces forage species (Wallmo et al. 1972). nilar trends in forage production have also en observed on lodgepole pine clearcuts in ntana (Basile and Jensen 1971). Wallmo ggests that new openings be cut periodically.

e alternative would be to cut about one-sixth a cutting block every 20 years in openings out four to five times tree height. Each rking Circle would be subdivided into a mber of cutting blocks (of at least 300 acres) that not all periodic cuts would be made in a gle year on a Working Circle. Such periodic ting would provide a good combination of mbers and species of palatable forage plants d the edge effect desired, while creating a eral-aged forest of even-aged groups, thus egrating wildlife habitat improvement with ber production.

servations on the Medicine Bow National rest in Wyoming indicate that both natural d cleared openings in lodgepole pine forests heavily used by American elk [*Cervus adensis canadensis* (Erxleben) Reynolds] for zing and calving.[2] The size of opening does t appear to be critical, but openings inter-rsed with standing timber that can be used ruminating, resting, and hiding are preferred. ce small openings cut in the canopy are not ely to retain a high proportion of palatable age species for long periods of time, new enings should be cut while allowing the older es to regenerate. Another alternative would be extend the size of the smaller (two acres or) natural openings, and periodically harvest remaining stand under some form of partial ting.

ner wildlife, including nongame animals, living odgepole pine forests are affected by the way se forests are handled. In general, their bitat requirements include a combination of nings and high forests to provide food, cover, and edge. With protection from wildfires many stands have become denser, and reproduction has filled in the openings. Some reduction in stand density is needed to create or improve wildlife habitat. Small, irregular openings (about four to five times tree height) cut in the canopy at periodic intervals, would open up the stand and provide the food, cover, and edge needed.

Recreation

Permanent forest cover — at least in part — is preferred in travel influence zones, and in areas of high recreational value and outstanding scenic beauty. Unfortunately, old-growth lodgepole pine stands are not likely to persist in a sound condition indefinitely. Where stand conditions and wind, insect, and disease problems permit, some form of partial cutting is one way that forest cover can be retained while at the same time replacing the old with a new stand. However, the visual impact of logging operations — haul roads, damage to residual trees, and slash and debris — must be minimized. In situations where there is no alternative to clearcutting, and the environmental impact of clearcutting is unacceptable, there is no choice but to leave the stands uncut.

To reduce the sudden and severe visual impact on the landscape viewer, openings cut in stands for timber and water production, wildlife habitat improvement, and recreation (ski runs) should be a repetition of natural shapes, visually tied together to create a balanced, unified pattern that will complement the natural landscape (Barnes 1971). This is especially important for those openings in the **middle** and **background** that can be seen from distant views. The **foreground** should be maintained in high forests under some partial cutting system (again, where stand conditions and wind, insect, and disease problems permit).

CHARACTERISTICS OF THE TYPE

The lodgepole pine type is generally pictured as an even-aged, single-storied, overly dense forest, varying in age from place to place but uniform in age within any given stand. This is true only on those areas where favorable fire, seed, and climatic conditions once combined to produce a substantial number of seedlings (Lexen 1949). Elsewhere, lodgepole pine grows on a wide range of sites with a great diversity of stand conditions and characteristics. This diversity complicates

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rsonal communication with A. Lorin Ward, Wildlife ologist, Rocky Mountain Forest and Range Experi-ent Station, Laramie, Wyoming.

the modification of silvicultural systems for multiple use. Lodgepole pine can occur as two-aged, single- or two-storied stands; three-aged, two- or three-storied stands; and even-aged to broad-aged, multi-storied stands (Tackle 1955). Multi-storied stands, and to a lesser extent two- and three-storied stands, generally resulted from either scattered trees that produced seed for subsequent development of the stand, or from the gradual deterioration of the old-growth associated with "normal" mortality from wind, insects, and diseases.

Most ecologists consider the successional status of lodgepole pine to be seral if it is only a temporary occupant of the site. In those situations, stands of mixed overstory composition or with appreciable amounts of advanced reproduction of other species are not uncommon. Pine is ultimately replaced by Engelmann spruce (*Picea engelmannii* Parry) and subalpine fir [*Abies lasiocarpa* (Hook.) Nutt.] at higher elevations, and Rocky Mountain Douglas-fir [(*Pseudotsuga menziesii* var. *glauca* (Biessn.) Franco] at lower elevations. On the other hand, many lodgepole pine stands are the result of catastrophic fires, and some areas have burned so often and so extensively that they are nearly pure pine. In those situations, lodgepole pine is maintained on the area as a sub-climax because there is no seed for the normal climax species (Tackle 1961, 1964a).

In stands of pure pine of medium to high density, there is seldom any understory of reproduction, while in low-density stands there may be an understory of young trees. If this reproduction has been suppressed for a long time, it seldom responds to release. Mixed stands can be either 1) pure pine, 2) pine, spruce, and subalpine fir, or 3) pine and Douglas-fir in the overstory, and the climax species in the understory. Spruce and subalpine fir reproduction suppressed for long periods are able to respond to release and make acceptable growth.

HISTORY OF PARTIAL CUTTING

From the early 1900's to about 1945, timber harvests in the lodgepole pine type on the National Forests of the central Rocky Mountains could generally be described collectively as "partial cutting." The usual procedure was to mark stands for the "selective" removal of special products. Cutting was usually heavy because everything salable was often marked removal. Nearly 40 years of observat research, and experience with partial cut provide some information on the capabili and limitations of existing stands to main permanent high forest cover.

In general, heavy partial cutting (removal more than 50 percent of the total basal ar and under some conditions any kind of pa cutting, was not successful in old-growth sta as a means of arresting stand deterioration. example, residual trees on the Fraser Exp mental Forest suffered heavy mortality wi about 60 percent of the total basal area removed by either individual tree selection modified seed-tree cutting (Alexander 196 Similar results followed heavy partial cut elsewhere in the central Rocky Mountains, in the northern and Canadian Rockies (Bl 1957, Hatch 1967, LeBarron 1952). Even wh mortality was not a serious problem, he partial cutting often left the older, decad stands in such poor condition that not only there little or no growing stock available another cut, but the stands had little appeara of permanent forest cover (Tackle 1964a).

The principal cause of mortality was usua windfall, and it generally increased as intensity of cutting increased. Mountain p beetle outbreaks caused heavy losses in so instances, and beetles continue to be a seri and often unpredictable threat to lodgepole p forests. In addition, many stands were infec with dwarf mistletoe, and partially opening the stand intensified the infection on resid trees. They in turn infected the new rep duction, leading to infection centers in the n generation. These heavily infected stands ar serious lodgepole pine management problem.

Where substantial reserve volumes were le partial cutting was successful in some instan in the sense that the residual stand did not bl down. On the Fraser Experimental Fore windfall losses were light and other mortal negligible after partial cutting removed about percent of the total basal area by a modifi shelterwood cut, even though the stands w exposed to windstorms that nearly destroy adjacent, partially cut stands with less resid basal area (Alexander 1966a). There are a numerous examples of early cuttings on ma National Forests in Colorado and Wyoming wh a light to moderate shelterwood cut th

Heavy windfall in lodgepole pine on the Fraser Experimental Forest, Colorado after partial cutting that removed about 60 percent of the original basal area.

emoved 30 to 40 percent of the total basal area lid not result in excessive mortality. The penings created have regenerated to either new odgepole pine or the climax species. Where lwarf mistletoe infection in overstory trees was ght, the new pine stand is not heavily infected. imilar stands have originated from open-grown rees and stands that were opened up by nountain pine beetle infestations.

SUSCEPTIBILITY TO WIND, DISEASE, AND INSECTS

Windfall

n the central Rocky Mountains, lodgepole pine generally considered susceptible to wind- nrow, and the risk increases when the stand is pened up by partial cutting (Alexander 1966a, lason 1915a). While the tendency to wind- nrow is frequently attributed to a shallow root ystem, the development of the root system aries with soil and stand conditions. On deep ell-drained soils, trees have a better root ystem than on shallow or poorly drained soils. ith the same soil conditions, the denser the and the less windfirm are individual stems, ecause trees that have developed together in ense stands over long periods of time mutually pport each other, and do not have the roots, bles, and crowns to withstand exposure to the ind if opened up drastically. The risk of blowdown is also greater in stands with defective roots and boles. The presence of old windfalls is a good indication of lack of windfirmness. Furthermore, regardless of how stands are cut or the soil and stand conditions, the risk of blowdown is greater on some exposures than others. The following windfall risk situations based on exposure have been identified by Mason (1915b) and Alexander (1964, 1967).

Low Windfall Risk Situations

1. Valley bottoms except where parallel to the prevailing winds, and all flat areas.
2. All lower and gentle middle north- and east-facing slopes.
3. All lower and gentle middle south- and west-facing slopes that are protected by considerably higher ground not far to windward.

Moderate Windfall Risk Situations

1. Valley bottoms parallel to the direction of prevailing winds.
2. All lower and gentle middle south- and west-facing slopes not protected to the windward.
3. Moderate to steep middle and all upper north- and east-facing slopes.
4. Moderate to steep middle south- and west-facing slopes protected by considerably higher ground not far to windward.

High Windfall Risk Situations

1. Ridgetops.
2. Moderate to steep middle south- and west-facing slopes not protected to the windward, and all upper south- and west-facing slopes.
3. Saddles in ridgetops.

The risk of windfall in these situations is increased at least one category by such factors as poor drainage, shallow soils, and defective roots and boles. All situations become high risk if exposed to special topographic situations such as gaps and saddles in ridges at higher elevations to the windward that can funnel wind into the area.

Dwarf Mistletoe

Surveys in Colorado and Wyoming show that from 30 to 60 percent of the commercial lodgepole pine forests are infected to some degree by dwarf mistletoe (Hawksworth 1958). Dwarf mistletoe reduces growth and increases mortality (Gill and Hawksworth 1964). It also drastically reduces seed production in infected trees. The mortality rate depends largely on the age of the host tree when attacked. Young trees die quickly, while older trees with well-developed and vigorous crowns may not show appreciable effects for years after the initial infection. Dwarf mistletoe is most damaging in stands that have been partially opened up by cutting, mountain pine beetles, or windfall, and of least consequence on regenerated burns following catastrophic fires (Gill and Hawksworth 1964). Heavily infected old-growth stands frequently have only about half the board-foot volume of comparable uninfected stands (Hawksworth 1958).

The disease is difficult to detect in recently infected stands because trees show no abnormalities except for the inconspicuous shoots on branches and main stems. On the other hand, where the parasite has been present for a long time, stands will have one or more heavily damaged centers characterized by many trees with witches' brooms, spike-tops, and an above-average number of snags with remnants of brooms (Gill and Hawksworth 1964).

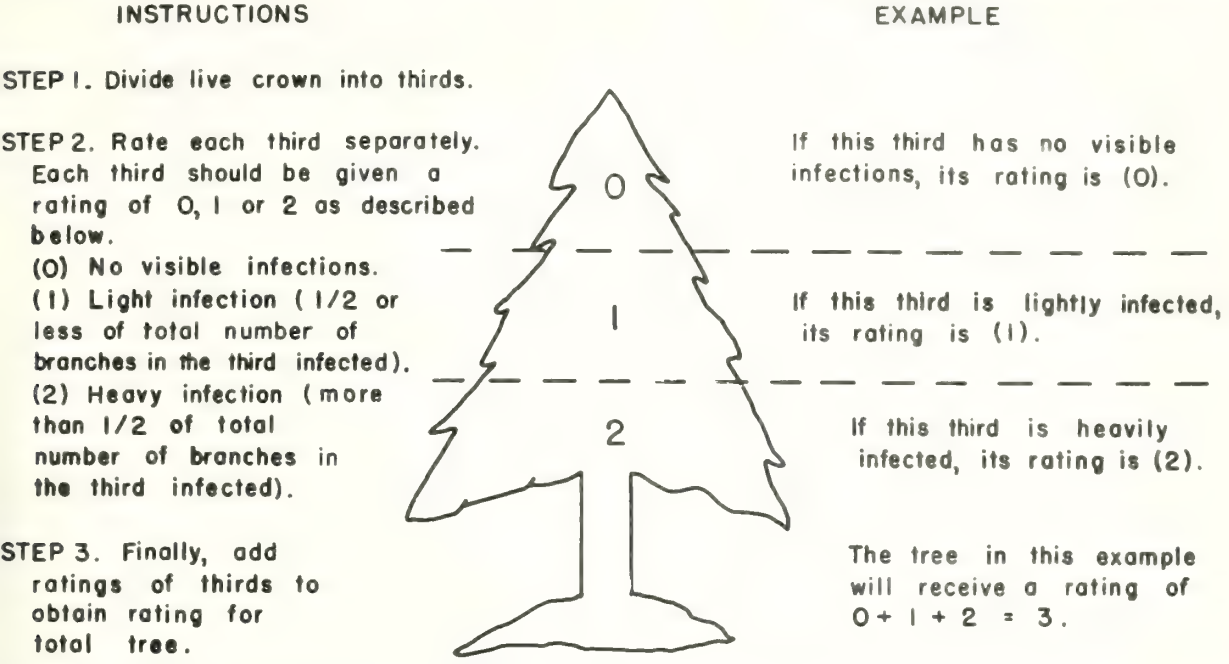
Although optimum development is favored by a vigorous host, and the most vigorous trees in a stand suffer the most damage, the frequency of infection is usually higher on poor than good sites. Furthermore, where site index (Alexande 1966c) is 70 or greater, only the middle an lower crowns of dominants and codominants ar susceptible to heavy infection, but trees in th intermediate or lower crown classes ar susceptible to heavy infection throughout the crowns. Where the site index is below 70, a crown classes are susceptible to heavy infectio throughout the crowns.[3] In Colorado an Wyoming, dwarf mistletoe has an altitudin limit about 300 to 500 feet below the upp limit of commercial lodgepole pine forests. Th means that in some areas, considerable lodgepo pine lies in a dwarf mistletoe-free zone (Gill ar Hawksworth 1964).

Separation of the old and new stands by clea cutting and felling unmerchantable residual tre appears to be the best way to control dwa mistletoe. In areas of high tree values such recreational, administrative, and homesites, may be possible to prune infected branches fro lightly infected trees, but heavily infected tre must be cut. Partial cutting and thinni generally create ideal conditions for maximu damage and should be avoided where possib unless the infection is light. To quantify t severity of infection, Hawksworth (196 developed the six-class mistletoe rating syste The average stand rating can be estimated b determining the percentage of trees infected the stand. The approximate relationship average stand rating to proportion of tre infected in several mature stands was:

Average stand mistletoe rating	Percent of tr infected
1	50
2	70
3	90
4	97
5	99
6	100

These ratings are used later in this paper un "Modifications to Cutting Practices Imposed Disease and Insect Problems" to assist in det mining which stands might be partially without severe damage to the residual trees.

[3] *Personal communication with Frank G. Hawkswo Plant Pathologist, Rocky Mountain Forest and Ra Experiment Station, Fort Collins, Colorado.*


INSTRUCTIONS
EXAMPLE
STEP 1. Divide live crown into thirds.
STEP 2. Rate each third separately. Each third should be given a rating of 0, 1 or 2 as described below.
(0) No visible infections.
(1) Light infection (1/2 or less of total number of branches in the third infected).
(2) Heavy infection (more than 1/2 of total number of branches in the third infected).
STEP 3. Finally, add ratings of thirds to obtain rating for total tree.
0
1
2
If this third has no visible infections, its rating is (0).
If this third is lightly infected, its rating is (1).
If this third is heavily infected, its rating is (2).
The tree in this example will receive a rating of 0 + 1 + 2 = 3.

e 6-class mistletoe rating system (Hawksworth 1961).

Comandra Blister Rust

is canker disease (caused by *Cronartium nandrae* Pk.) commonly occurs in the central cky Mountains, but damage has been most ensive in northern Wyoming (Peterson 1962). ad tops and flagging branches resulting from dling are the most conspicuous symptoms til dead trees begin to appear. On larger stem ections, cankers with an abundance of yellow, ed resin are another conspicuous symptom ielke et al. 1968). The disease cannot pass ectly from pine to pine but requires an ermediate host [*Comandra umbellata* (L.) tt.].

e damage from Comandra rust is usually not ctacular, but trees of all sizes and ages are ceptible (Peterson 1962). Seedlings may be ed in a relatively short time. In older trees, time between initial infection and death may 25 or more years because the infection enters trunk by way of the branches and the rate of ead is slow. Under conditions favorable to the t, stands may be heavily damaged over ited areas. In those stands, from 30 to 40 cent of the living and dead trees will have kers, and about half the cankered trees will have spike-tops (Krebill 1965). Usually, however, the infection is lighter and scattered through the stand (Peterson 1962).

Sanitation salvage cutting is about the only practical way of controlling the disease in forest stands (Mielke et al. 1968). In areas of high tree values it may be possible to prune infected branches from lightly infected trees, but heavily infected trees should be cut. Partial cutting and thinning appear well adapted to the control or reduction of Comandra rust, even in heavily damaged stands, because the disease is not passed from pine to pine and only the trees with stem infections need to be removed.

Mountain Pine Beetle

The mountain pine beetle (*Dendroctonus ponderosae* Hopk.) is the most serious insect pest in mature to overmature lodgepole pine stands in the Rocky Mountains. Epidemics have occurred throughout recorded history (Roe and Amman 1970), and extensive outbreaks are now in progress in northern Wyoming. Less extensive but severe outbreaks are underway in southern Wyoming and northern Colorado, where a large

number of old-growth stands that have been protected from wildfires are now reaching a high degree of susceptibility to attack.

Mountain pine beetles feed and breed in the phloem layer. The first indications of attack are pitch tubes on the trunk where beetles have entered and boring dust in the bark crevices and around the base of the tree. Trees successfully attacked in the summer usually begin to fade the following spring. Needles change from green to yellow green, sorrel, and finally rusty brown before dropping off (McCambridge and Trostle 1970).

Not all stands are equally susceptible to attack. Epidemic outbreaks are usually associated with stands that contain at least some vigorous, thick-phloemed trees 14 inches in diameter and larger (Cole and Amman 1969, Roe and Amman 1970). As the larger trees are killed, the beetles must attack smaller diameter trees, and the outbreak subsides because the phloem of these trees is not thick enough to provide a food supply. Trees smaller than 6.0 inches d.b.h. are rarely killed.

Natural factors, such as a sudden lowering of fall temperature or prolonged subzero winter temperatures, nematodes, woodpeckers, and parasites, may reduce populations but they cannot be relied upon to control outbreaks (McCambridge and Trostle 1970). Chemical control is expensive and often is only a holding action until potentially susceptible trees can be disposed of by other means. The only alternatives left to the manager in heavily infested stands where most of the trees are 10 inches in diameter and larger are to 1) fell and salvage the infested trees, burn the green culls and unmerchantable portions of trees, and regenerate a new stand, or 2) let the infestation run its course uncontrolled. On the other hand, in infested stands with a good stocking of trees in the smaller diameter classes, partial cutting that removes the vigorous, larger trees with thick phloem appears well adapted to regulating mountain pine beetle losses.

A TREE CLASSIFICATION FOR MARKING IN PARTIALLY CUT STANDS

In developing partial cutting practices, knowledge of individual tree characteristics will assist in establishing marking guides. A classification scheme for lodgepole pine in Colorado a Wyoming based on the area, length, and vigor individual tree crowns (Taylor 1939) described below:

Vigor class A

1. Crown area: 30 percent or more of t "extreme outline" of vigor class A.
2. Crown length: 50 percent or more of the bo length.
3. Crown vigor: Dense, full, good col pointed.

Vigor class B

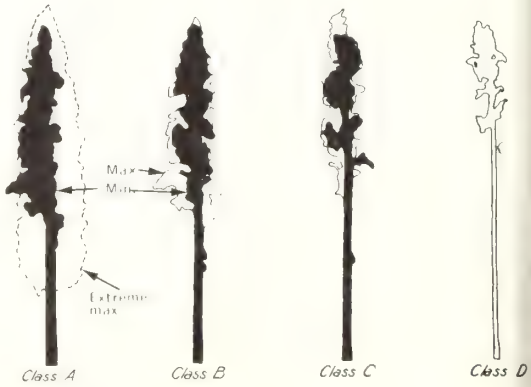
1. Crown area: Usually more than 30 perce but less than 50 percent of the "extre outline" of vigor class A.
2. Crown length: Usually more then 50 perce but usually less than 60 percent of the bo length.
3. Crown vigor: Moderately dense, good col pointed or slightly rounded.

Vigor class C

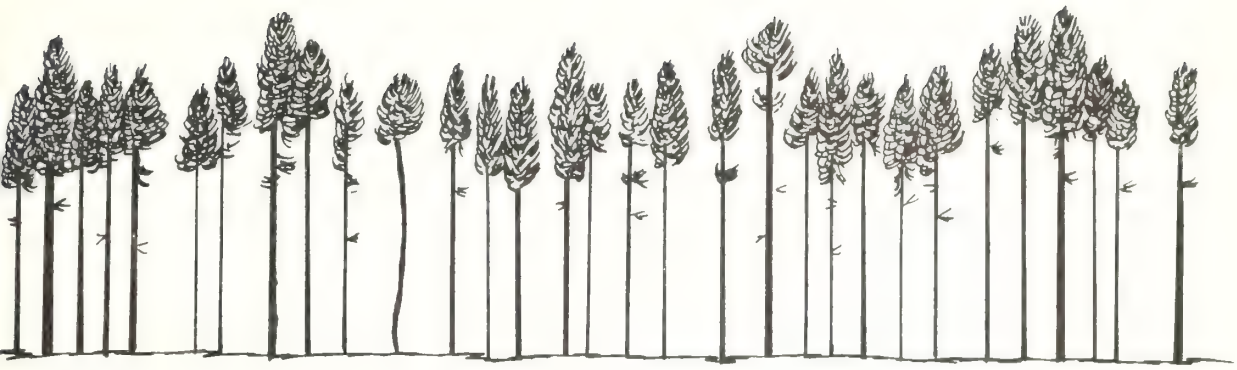
1. Crown area: 15 to 30 percent of t "extreme outline" of vigor class A.
2. Crown length: 40 to 50 percent of the bo length except for trees with above avera vigor, when 20 percent of the bole length sufficient.
3. Crown vigor: Sparse, bunchy, poor col never pointed.

Vigor class D

1. All live trees of poorer vigor than class Includes trees in classes A, B, and C outli but with dead or dying tops.



Tree vigor classes (Taylor 1939).



Single-storied stand.

though the classification was developed more an 30 years ago, is subjective, and places many ees of old-growth stands in vigor classes C and it nevertheless provides useful guidelines in termining the kinds of trees that should be cut left, depending on stand, insect and disease nditions, and management objectives.

STAND DESCRIPTIONS

e following stand descriptions are suggested as eliminary guidelines for differentiating mature overmature lodgepole pine stands. They were veloped largely by Tackle (1955) for the ermountain Region, but have been modified observation and experience in the central cky Mountains. Stands are pure pine unless herwise indicated:[4]

Single-Storied Stands[5]

May appear to be even-aged, but often contains more than one age class, occasionally may even be broad-aged.

Codominants form the general level of the canopy, but the difference in height between dominants, codominants, and intermediates is not as great as in spruce-fir stands.

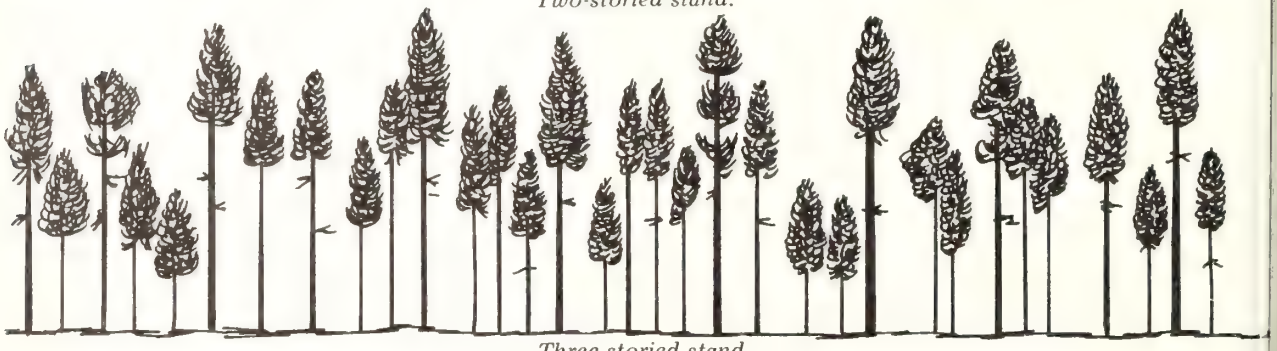
3. If even-aged in appearance: (a) There is a small range in diameter classes and crown length. (b) Live crown length of dominants and codominants is generally short to medium (30 to 60 percent of the total tree height and boles are generally clear for 10 to 40 percent of total tree height). (c) There are few coarse-limbed trees in the stand.
4. With two or more age classes, the younger trees usually have finer branches, smaller diameters, longer live crown, and less clear bole than older trees.
5. Stocking is generally uniform.
6. Usually does not have a manageable stand of advanced reproduction.[6]
7. In **mixed stands**, the overstory is either (a) pure pine or (b) pine and Engelmann spruce, subalpine fir, or Douglas-fir, with advanced reproduction of species other than pine that may or may not be a manageable stand.

mixed stand is one where either less than 80 percent the overstory basal area is lodgepole pine, or the verstory is pine with an understory of a different ecies.

eproduction less than 4.5 feet tall is not considered a and story in these descriptions.

[6] Since any kind of cutting may destroy as much as one-half of the advanced reproduction, even with careful logging, at least 600 seedlings and saplings per acre of good form and vigor, and free of defect, must be present to be considered a manageable stand.

Two-storied stand.



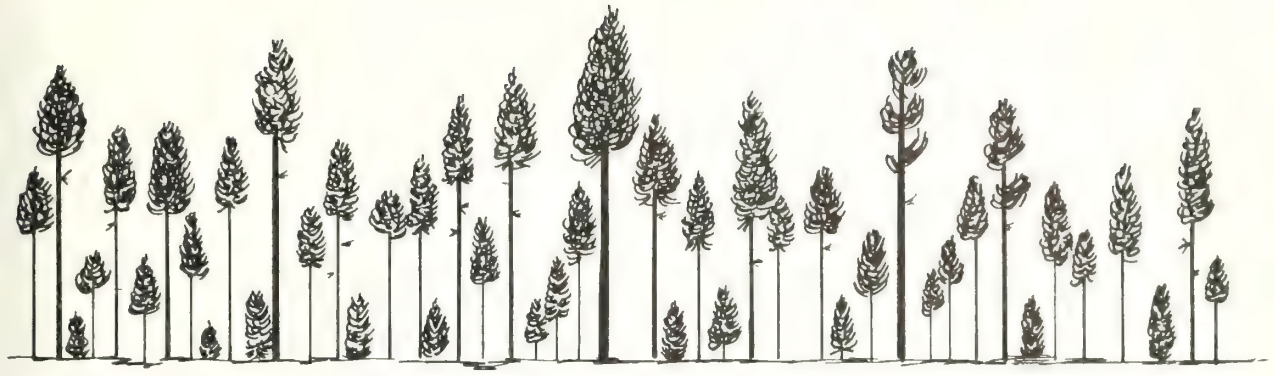
Three-storied stand.

Two-Storied Stands

1. May appear to be two-aged, but can contain more than two age classes.
2. Top story—dominants, codominants, and intermediates—resembles a single-storied stand.
3. Second story is composed of younger trees of smaller diameter — small saw logs, poles, or saplings — than top story, but is always below and clearly distinguishable from the overstory. Trees in the second story are overtopped and may or may not be suppressed.
4. If more than two-aged, the overstory usually contains at least two age classes. The younger trees are finer limbed and may be smaller in diameter than the older trees. Second story may also contain more than one age class.
5. Stocking of overstory may be irregular, but overall stocking is usually uniform.
6. Usually does not have a manageable stand of advanced reproduction.
7. In mixed stands, overstory is usually pure pine, but occasionally may be pine and spruce or Douglas-fir. Second story is usually spruce and fir at higher elevations and Douglas-fir at lower elevations.
8. Stocking in **mixed stands** may vary from uniform to irregular.
9. **Mixed stands** may have a manageable stand of advanced reproduction of species other than pine.

Three-Storied Stands

1. May appear three-aged; can contain mo than three age classes but is seldom broa aged.
2. Top story resembles a single-storied sta except that there are fewer trees.
3. Second and third stories consist of younge smaller diameter trees. Second story may l small saw logs or large poles, while the thi story is likely to be composed of small pol or saplings. Second and third stories are ove topped, and some trees may be suppressed.
4. Overall stocking is likely to be uniform, b stocking of any story may be irregular.
5. Usually does not have a manageable stand advanced reproduction.
6. In **mixed stands** the top story may be eith pure pine or a mixture of pine and oth species. Second story is usually spruce a subalpine fir at higher elevations, or Dougl fir at lower elevations. May occasional contain some pine, but is rarely pure pin Third story is almost always composed species other than pine.
7. Stocking in **mixed stands** can vary fro uniform to irregular.
8. **Mixed stands** often have a manageable sta of advanced reproduction of species oth than pine.



Multi-storied stand.

Multi-Storied Stands

1. Usually broad-aged with a wide range in diameters.
2. If stands developed from relatively few individuals following disturbance, the overstory trees are coarse-limbed. Fill-in trees are better formed and finer limbed. Vigor of overstory trees varies from poor to good.
3. In stands that developed from deterioration of single- or two-storied stands, the overstory trees may be no limbier than the fill-in trees. Nearly all of the healthy, faster growing trees are below saw log size.
4. Stocking may be irregular.
5. May have a manageable stand of advanced reproduction.
6. In a **mixed stand,** the overstory may be pure pine or either pine, spruce, and fir at higher elevations or pine and Douglas-fir at lower elevations. Understory trees have the same characteristics as pure stands except that the composition is likely to be species other than pine.
7. Stocking in **mixed stands** is more likely to be irregular.
8. **Mixed stands** frequently have a manageable stand of advanced reproduction of species other than pine.

CUTTING PRACTICES

The kinds of stands desirable to meet different management objectives suggest certain cutting practices. However, such factors as stand conditions, windfall, insect and disease susceptibility, and the risk of potential fire damage, which vary from place to place on any area, limit the handling of stands. Furthermore, the economics of harvesting, manufacturing, and marketing wood products in the central Rocky Mountains imposes further limitations on cutting practices. Cutting to bring old-growth lodgepole pine under management is likely to be a compromise between what is desirable and what is possible. Management may involve a combination of clearcutting small areas, several partial cutting treatments, and no cutting on many areas. Initial cuttings will be in the form of intermediate cuts on some areas, sanitation salvage cuts on others, and regeneration cuts on still other areas.

The recommendations that follow are keyed to stand descriptions and windfall risk situations. Additional constraints imposed by insect and disease problems are considered at the end of this section. The recommendations are suggested as guides to **initial cutting** with the objective of maintaining forest cover **after the first cut. Accurate appraisal** of the capabilities and limitations of each stand, **careful marking** of individual trees or groups of trees to be removed, and **close supervision** of logging are required. Stands are considered pure pine unless otherwise indicated.

Single-Storied Stands

Usually these are the least windfirm because the trees have developed together over long periods of time and mutually protect each other from the wind.

Low Windfall Risk Situations

1. The first cut can remove about 30 percent of the basal area on an individual-tree basis.[7]

[7] *As a practical matter, small trees that do not represent significant competition to the remainder of the stand may be excluded from the computation of the basal area.*

This initial entry is an **intermediate cut** that resembles the first step of a three-cut shelterwood, since it probably does not open up the stand enough for pine reproduction to become established in significant numbers. Overstory trees are all about equally susceptible to blowdown; therefore the general level of the canopy should be maintained by removing some trees in each overstory crown class. The cut should come from C and D vigor class trees, but openings larger than one tree height in diameter should be avoided by distributing the cut over the entire area. In **mixed stands**, if the overstory is pure pine, handle as a pure stand; if the overstory is of mixed composition, cut as much of the basal area recommended in pine as is possible to release the climax species.

2. The usual uniform arrangement of individual trees in single-storied stands is not well adapted to removing trees by **group selection cutting.** Occasionally, however, natural openings do occur when stands begin to break up. Furthermore, small openings may be desirable to meet management objectives. An alternative to removing trees on an individual basis would be to remove about 30 percent of the basal area in groups. Openings should be kept small, not more than one to two times tree height in diameter; not more than one-third of the area should be cutover at any one time. This kind of cutting should be used only in stands where insect and disease problems are minimal.

Moderate Windfall Risk Situations

1. The first cut should be limited to a light intermediate cutting that removes about 20 percent of the basal area on an individual-tree basis. The objective is to open up the stand enough to allow the remaining trees to develop windfirmness, but provision should be made to salvage blowdowns. This type of cutting resembles a **sanitation cut** in that the lowest vigor and poorest risk trees should be removed, but it is important that the general level of the overstory canopy be maintained intact. **Mixed stands** should be handled the same as in low wind risk situations, except that less basal area will be removed.

High Windfall Risk Situations

1. The choice is limited to removing all trees or leaving the stand uncut. Cleared openings can be up to about 5 acres, interspersed with uncut areas. Cutover areas should not exceed about one-third of the total in this risk situation.

Two- and Three-Storied Stands

Trees in the top story are usually more windfirm than those in a single-storied stand. Trees in the second and third stories are usually less windfirm than trees in the top story.

Low Windfall Risk Situations

1. The first cut can remove up to 50 percent of the basal area in **two-storied stands** (providing not more than half of the basal area removed comes from the top story), and up to 40 percent of the basal area from **three-storied stands.** This cutting is as heavy as the first **regeneration** cut of a two-cut shelterwood but marking follows the rules for individual tree selection. Heavier cutting may be possible in three-storied stands, but the appearance of a continuous overstory is not likely to be retained. Trees removed should be in vigor classes C and D insofar as possible but since the top story is likely to be more windfirm, selected dominants and codominants should be left even when they are in vigor classes C and D, if they do not have dead or dying tops. Avoid cutting holes in the canopy larger than one tree height in diameter by distributing the cut over the entire area. In **mixed stands,** if the top story or, rarely, the first and second stories are pure pine, handle as a pure stand. If the top story is of mixed composition, cut as much of the basal area to be removed in pine as is possible and release the climax species, but do not cut all of the pine if it is needed to maintain the overstory.
2. In **pure** or **mixed** stands with irregular stocking that may have resulted from the breakup of single-storied stands, old beetle attacks, or windfall losses, an alternative first cut can remove about 40 percent of the basal area in a **modified group selection.** Heavier cuts may be possible, but the appearance of a continuous overstory canopy may not be retained. The group openings can be larger (two to three times tree height) than in single-storied stands, but the area cutover should not exceed about one-third of the total. Openings should be irregular in shape without wind-catching indentations in the borders. This kind of cutting is not applicable in pure stands where mountain pine beetle

dwarf mistletoe impose limitations, because the interval between initial cutting and final harvest is likely to be too long to prevent serious mistletoe infection of new reproduction and/or loss of beetle-susceptible trees.

loderate Windfall Risk Situations

. The first cut should be an **intermediate harvest** that removes not more than 30 percent of the basal area on an individual-tree basis. Predominants, and codominants and intermediates with long live crowns should be removed first. The remaining cut should then come from trees in vigor classes C and D. Maintain the general level of the canopy by not cutting holes larger than one tree height in diameter in the canopy. Provision should be made to salvage blowdowns. **Mixed stands** should be handled as in low wind risk situations except that less basal area should be removed.

igh Windfall Risk Situations

. The choice is limited to either removing all the trees or leaving the stand uncut. Cleared openings can be up to about five acres, interspersed with uncut areas. The cutover area should not exceed about one-third of the total in this risk situation.

Multi-Storied Stands

hese are usually the most windfirm stands, en where they have developed from the eterioration of single- and two-storied stands. y the time they have reached their present ndition, the remaining overstory trees are kely to be windfirm.

ow to Moderate Windfall Risk Situations

There is considerable flexibility in harvesting these stands. All size classes can be cut, with emphasis on either the largest or smallest trees in the stand. The first cut can range from an overwood removal to release the younger growing stock to a thinning from below to improve the spacing of the most vigorous of the larger trees. Thereafter, cutting can be directed toward either even-aged or uneven-aged management. In **mixed stands** the first cut should be an overwood removal of the pine to release the climax species. The understory trees should be thinned to improve spacing.

High Windfall Risk Situations

1. The safest first cut is an overwood removal with a light thinning from below to obtain a wider spaced, more open stand that can develop windfirmness. Thereafter, cutting can be directed toward either uneven- or even-aged management.

Modifications to Cutting Practices Imposed by Disease and Insect Problems

Dwarf Mistletoe

1. Cut only in stands where the average mistletoe rating is two or less (less than about two-thirds of the trees are infected), and remove only the percentage of basal area recommended for the stand description and windfall situation. In **single-storied** stands, where site index is 70 or above, trees in the intermediate and lower crown classes should be removed in preference to dominants and codominants. If site index is below 70, trees in all crown classes are about equally susceptible to infection. In **two-** and **three-storied** stands, as much of the cut as is possible should come from the second and third stories because these trees are likely to be more heavily infected than the top story. To minimize infection of new reproduction in **single-**, **two-**, and **three-storied** stands, the final overstory removal should be made when the new reproduction is tall enough to provide a forest aspect, but should not exceed 30 years after the regeneration cut when the average mistletoe rating is one, or 20 years when the rating is two. Provision should be made to sanitize the young stand at the time of final harvest. In **multi-storied** stands, the safest procedure is an overwood removal with a cleaning and thinning from below.
2. In old-growth stands with an average mistletoe rating of greater than two, any partial cutting, thinning, or cleaning is likely to intensify the infection. The safest procedure, therefore, is to either remove all of the trees and start a new stand or leave the stand uncut. If the manager chooses to make a partial cut for any reason, the initial harvest should be heavy enough to be a regeneration cut. All residual trees must be removed

within 10 years after the first cut, and provision made to sanitize the young stand at that time.

Comandra Blister Rust

1. Cut as many trees with stem cankers and spike-tops as possible without removing more than the recommended basal area or cutting large openings in the canopy. Since the rate of spread in mature trees is relatively slow and the disease is not transmitted from pine to pine, leaving a few infected trees is less of a risk than opening up the stand too much.

Mountain Pine Beetle

1. If the insect is present in the stand at an endemic level, or in adjacent stands in sufficient numbers to make successful attacks, and:
   a. Less than the recommended percentage of basal area to be removed is in susceptible trees, any attacked tree and all of the most susceptible trees should be removed in the first cut. This will include most of the trees 12 inches d.b.h. and larger, and all trees 10 to 12 inches d.b.h. in vigor classes A and B. Provision should be made to salvage attacked trees, and a second cut should be made about 10 years after the first cut.
   b. More than the recommended percentage of basal area to be removed is in susceptible trees, the manager has three options: 1) remove all the trees, 2) remove the recommended basal area in attacked and susceptible trees and accept the risk of future losses, or 3) leave the stand uncut. If the stand is partially cut or left uncut, some trees from 7 to 12 inches d.b.h. and most trees below 7 inches d.b.h. will survive.
2. If the stand is sustaining an infestation that is building up, and the manager chooses to either partially cut or leave the stand uncut, he must accept the risk of an outbreak that could destroy most of the merchantable stand.

REGENERATION PRACTICES

The primary purposes of the cutting practices suggested are to aid the forest manager in maintaining continuous forest cover of lodgepole pine while minimizing the limitations to partial cutting imposed by silvical requirements, stand conditions, wind, insects, and diseases.

Nevertheless, the reductions made in the ov story canopy by removing 40 percent or more the basal area by **modified shelterwood**, openings cut in the canopy by modified gro **selection**, are large enough to permit n reproduction to become established, providi there is a sufficient seed supply and the seedb is compatible with germination and surviv Furthermore, this kind of cutting is hea enough that some treatment of logging slash a unmerchantable material is usually necessary desirable.

Lodgepole pine varies considerably in its co habit, and **each stand** should be **examined befo cutting** to determine serotiny. Individual tre generally bear either serotinous or no serotinous cones,[8] and at least 40 percent of th trees should bear serotinous cones before a sta can be considered to have the closed-cone hab

In general, throughout much of Colorado a southern Wyoming, seed is stored in clos cones that open only when exposed to relative high temperatures (Alexander 1966b, Tack 1961). Dispersal comes largely from con attached to the logging slash or scattered on th ground. How and when the slash is treat directly influences regeneration success. Trea ment should not be attempted until the con have had time to dry out and open up. Where residual stand remains, treatment should l limited to lopping and scattering, chipping alo the roadways, and hand piling and burning minimize damage. In cleared openings, it may l possible to machine pile the concentrations f burning.

In northern Wyoming, cones generally open maturity and seeds are dispersed by the wind the usual manner. Most seeds will fall with about 200 feet of the source (Boe 1956, Tack 1964b). In those situations, seed for regene ation comes from trees cut on the area, le standing on the area, or standing around th perimeter. Slash should be handled in the sam manner as in closed-cone stands, except that can be treated when green.

Scarification is usually necessary to remov heavy concentrations of duff and litter t prepare mineral soil seedbeds; it should be don during logging and slash treatment.

[8] *Lotan and Jensen (1970) classified lodgepole pin trees in the Northern Rockies and Intermountai Region as serotinous if they bore 90 percent or mo closed cones, and non-serotinous if they bore 9 percent or more open cones.*

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Guidelines are provided to aid the forest manager in developing partial cutting practices to maintain continuous forest cover in travel influence zones, and in areas of high recreational values or outstanding scenic beauty. These guidelines consider stand conditions, windfall risk situations, and insect and disease problems. These cutting practices may be also used in combination with small cleared openings to create the kinds of stands desirable for increased water yields, improvement of wildlife habitat, and to integrate timber production with other uses. On areas where timber production is the primary objective, clearcutting in small, dispersed units is the recommended method of harvesting trees.

Key Words: Forest cutting systems, *Pinus contorta*, stand condition, windfall risk, dwarf mistletoe, mountain pine beetle.

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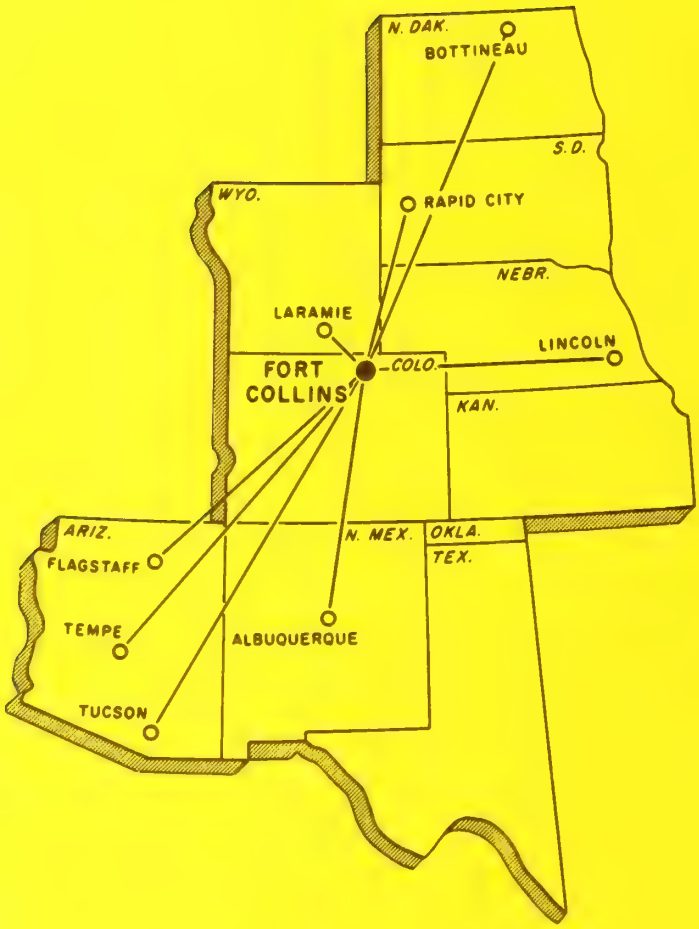
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NEBR.
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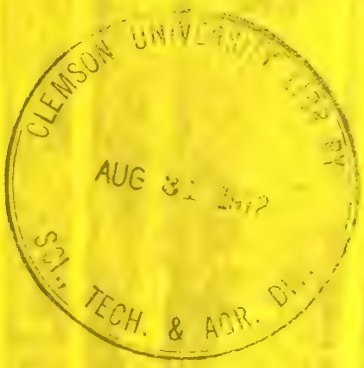
PARTIAL CUTTING PRACTICES IN OLD-GROWTH LODGEPOLE PINE

A Field Guide

by Robert R. Alexander



INTRODUCTION

This field guide was prepared to aid the forest manager in identifying different stand conditions and developing partial cutting practices needed to maintain permanent forest cover. Detailed information on tree and stand characteristics, windfall risk, insect and disease susceptibility, and cutting practices to integrate timber production with other uses is given in USDA Forest Service Research Paper RM-92, "Partial Cutting Practices in Old-Growth Lodgepole Pine."

WINDFALL RISK SITUATION

A. LOW RISK

1. Valley bottoms except where parallel to the prevailing winds, and all flat areas.

2. All lower and gentle middle north- and east-facing slopes.

3. All lower and gentle middle south- and west-facing slopes that are protected by considerably higher ground not far to windward.

B. MODERATE RISK

1. Valley bottoms parallel to the direction of prevailing winds.

2. All lower and gentle middle south- and west-facing slopes not protected to the windward.

3. Moderate to steep middle and all upper north- and east-facing slopes.

4. Moderate to steep middle south- and west-facing slopes protected by considerably higher ground not far to windward.

C. HIGH RISK

1. Ridgetops.

2. Moderate to steep middle south- and west-facing slopes not protected to the windward and all upper south- and west-facing slopes.

3. Saddles in ridgetops.

The risk of windfall in these situations is increased at least one category by such factors as poor drainage, shallow soils, and defective roots and boles. All situations become high risk if exposed to special topographic situations such as gaps and saddles in ridges at higher elevations to the windward that can funnel wind into the area.

MISTLETOE RATING SYSTEM

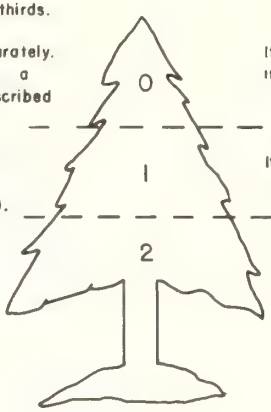
INSTRUCTIONS

STEP 1. Divide live crown into thirds.

STEP 2. Rate each third separately. Each third should be given a rating of 0, 1 or 2 as described below.
(0) No visible infections.
(1) Light infection (1/2 or less of total number of branches in the third infected).
(2) Heavy infection (more than 1/2 of total number of branches in the third infected).

STEP 3. Finally, add ratings of thirds to obtain rating for total tree.

EXAMPLE



If this third has no visible infections, its rating is (0).

If this third is lightly infe its rating is (1).

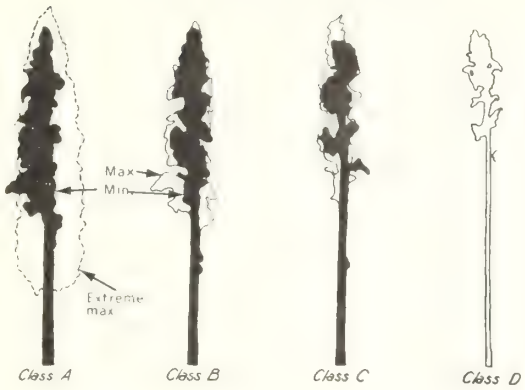
If this third is heavily infected, its rating is (

The tree in this examp will receive a rating 0 + 1 + 2 = 3.

The average stand rating can be estimated by determining the percentage of trees infected in the stand. The approximate relationship of average stand rating to proportion of trees infected in mature stands is shown below:

Average stand mistletoe rating	Percent of trees infected
1	50
2	70
3	90
4	97
5	99
6	100

TREE VIGOR CLASSES



A. VIGOR CLASS A

1. Crown area: 30 percent or more of the "extreme outline" of vigor class A.

2. Crown length: 50 percent or more of the bole length.

3. Crown vigor: Dense, full, good color, pointed.

B. VIGOR CLASS B

1. Crown area: Usually more than 30 percent but less than 50 percent of the "extreme outline" of vigor class A.

2. Crown length: Usually more than 50 percent but usually less than 60 percent of the bole length.

3. Crown vigor: Moderately dense, good color, pointed or slightly rounded.

C. VIGOR CLASS C

1. Crown area: 15 to 30 percent of the "extreme maximum" of vigor class A.

2. Crown length: 40 to 50 percent of the bole length except for trees with above-average vigor when 20 percent of the bole length is sufficient.

3. Crown vigor: Sparse, bunchy, poor color, never pointed.

D. VIGOR CLASS D

1. All live trees of poorer vigor than class C. Includes trees in classes A, B, and C outlines but with dead or dying tops.

SINGLE-STORY

A. STAND DESCRIPTION

1. May appear to be even-aged, but often contains more than one age class, occasionally may even be broad-aged.

2. Codominants form the general level of the canopy, but the difference in height between dominants, codominants and intermediates is not as great as in spruce-fir stands.

3. If even-aged in appearance: (a) There is a small range in diameter classes and crown length. (b) Live crown length of dominants and codominants is generally short to medium (30 to 60 percent of the total tree height and boles are generally clear for 10 to 40 percent of total tree height). (c) There are few coarse-limbed trees in the stand.

4. With two or more age classes, the younger trees usually have finer branches, smaller diameters, longer live crown and less clear bole than older trees.

5. Stocking is generally uniform.

6. Usually does not have a manageable stand of advanced reproduction.

7. In mixed stands, the overstory is either (a) pure pine or (b) pine and Engelmann spruce, subalpine fir or Douglas-fir, with advanced reproduction of species other than pine that may or may not be a manageable stand.

SUGGESTED CUTTING PRACTICES

These stands are usually the least windfirm because the trees have developed together over long periods of time and mutually protect each other from the wind.

1. Low windfall risk situations

   a. The first cut can remove about 30 percent of the basal area on an individual tree basis. This first entry is an intermediate cut that resembles the first step of a three-cut shelterwood since it probably does not open up the stand enough for pine reproduction to become established in significant numbers. Overstory trees are all about equally susceptible to blowdown, therefore, the general level of the canopy should be maintained by removing some trees in each overstory crown class. The cut should come from C and D vigor class trees, but avoid cutting openings larger than one tree height in diameter by distributing the cut over the entire area. In mixed stands, if the overstory is pure pine, handle as a pure stand, but if the overstory is of mixed composition, cut as much of the pine as possible (without exceeding the percentage of basal area recommended) to release the climax species.

   b. The usual uniform arrangement of individual trees in single-storied stands is not well adapted to removing trees by group selection cutting. Occasionally, however, natural openings do occur when stands begin to break up. Furthermore, small openings may be desirable to meet management objectives. An alternative to removing trees on an individual basis would be to remove about 30 percent of the basal area in groups. Openings should be kept small--not more than 1 to 2 times tree height in diameter--and not more than one-third of the area should be cutover at any one time. This kind of cutting should be used only in stands where insect and disease problems are minimal.

2. Moderate windfall risk situations

   a. The first cut should be limited to a light intermediate cutting that removes about 10 to 20 percent of the basal area on an individual tree basis. The objective is to open up the stand enough to allow the remaining trees to develop windfirmness, but provision should be made to salvage blowdowns. This type of cutting resembles a sanitation cut in that the lowest vigor and poorest risk trees should be removed, but it is important that the general level of the overstory canopy be maintained intact. Mixed stands should be handled the same as in low wind risk situations, except that less basal area will be removed.

3. High windfall risk situations

   a. The choice is limited to removing all trees or leaving the stand uncut. Cleared openings can be up to about 5 acres interspersed with uncut areas. Cutover areas should not exceed about one-third of the total.

TWO-STORY

A. STAND DESCRIPTION

1. May appear to be two-aged, but can contain more than two age classes.

2. Top story--dominants, codominants and intermediates resembles a single-storied stand.

3. Second story is composed of younger trees of smaller diameter--small saw logs, poles or saplings--than top story, but is always below and clearly distinguishable from the overstory. Trees in the second story are overtopped but may not be suppressed.

4. If more than two-aged, the overstory usually contains at least two age classes. The younger trees are finer limbed and may be smaller in diameter than the older trees. Second story may also contain more than one age class.

5. Stocking of overstory may be irregular, but overall stocking is usually uniform.

6. Usually does not have a manageable stand of advanced reproduction.

7. In mixed stands, overstory is usually pure pine, but occasionally may be pine and spruce or Douglas-fir. Second story is usually spruce and fir at higher elevations and Douglas-fir at lower elevations.

8. Stocking in mixed stands may vary from uniform to irregular.

9. Mixed stands often have a manageable stand of advanced reproduction of species other than pine.

SUGGESTED CUTTING PRACTICES

Trees in the top story are usually more windfirm than those in a single-storied stand. Trees in the second and third stories are usually less windfirm than trees in the top story.

1. Low windfall risk situations

   a. The first cut can remove up to 40 percent of the basal area in three-storied stands (providing not more than half of the basal area removed comes from the top story). This cutting is as heavy as the first or regeneration cut of a two-cut shelterwood, but marking follows the rules for individual tree selection. Trees removed should be in vigor classes C and D insofar as possible, but since the top story is likely to be more windfirm, selected dominants and codominants should be left even when they are in vigor classes C and D, if they do not have dead or dying tops. Avoid cutting holes in the canopy larger than one tree height in diameter by distributing the cut over the entire area. In mixed stands, if the top story or the first and second stories are pure pine, handle as a pure stand. If the top story is of mixed composition, cut as much of the basal area to be removed in pine as is possible and release the climax species, but do not cut all of the pine if it is needed to maintain the overstory.

   b. In pure or mixed stands with irregular stocking, an alternative first cut can remove about 40 percent of the basal area in a modified group selection. The group openings can be larger (2 to 3 times tree height) than in single-storied stands, but the area cutover should not exceed about one-third of the total. Openings should be irregular in shape without wind-catching indentations in the borders. This kind of cutting is not applicable in pure stands where mountain pine beetle or dwarf mistletoe impose limitations because the interval between initial cutting and final harvest is likely to be too long to prevent serious mistletoe infection of new reproduction and/or loss of beetle-susceptible trees.

2. Moderate windfall risk situations

   a. The first cut should be an intermediate harvest that removes not more than 30 percent of the basal area on an individual tree basis. Predominants, and codominants and intermediates with long live crowns should be removed. Maintain the general level of the canopy by not cutting holes larger than one tree height in diameter in the canopy. Provision should be made to salvage blowdowns. Mixed stands should be handled as in low wind risk situations except that less basal area will be removed.

3. High windfall risk situations

   a. The choice is limited to either removing all the trees or leaving the stand uncut. Cleared openings can be up to about 5 acres, interspersed with uncut areas. The cutover area should not exceed about one-third of the total.

THREE-STORY

A. STAND DESCRIPTION

1. May appear three-aged; can contain more than three age classes, but is seldom broad-aged.

2. Top story resembles a single-storied stand except that there are fewer trees.

3. Second and third stories consist of younger, smaller diameter trees. Second story may be small saw logs or large poles, while the third story is like to be composed of small poles or saplings. Second and third stories are overtopped, and some trees may be suppressed.

4. Overall stocking is likely to be uniform, but stocking of any story may be irregular.

5. Usually does not have a manageable stand of advanced reproduction.

6. In mixed stands the top story may be either pure pine or a mixture of pine and other species. Second story is usually spruce and subalpine fir at higher elevations, or Douglas-fir at lower elevations. May occasionally contain some pine, but is rarely pure pine. Third story is almost always composed of species other than pine.

7. Stocking in mixed stands can vary from uniform to irregular.

8. Mixed stands often have a manageable stand of advanced reproduction of species other than pine.

SUGGESTED CUTTING PRACTICES

Trees in the top story are usually more windfirm than those in a single-storied stand. Trees in the second story are usually less windfirm than trees in the top story.

1. Low windfall risk situations

   a. The first cut can remove up to 50 percent of the basal area in two-storied stands (providing not more than half of the basal area removed comes from the top story). This cutting is as heavy as the first or regeneration cut of a two-cut shelterwood, but marking follows the rules for individual tree selection. Trees removed should be in vigor classes C and D insofar as possible, but since the top story is likely to be more windfirm, selected dominants and codominants should be left even when they are in vigor classes C and D, if they do not have dead or dying crowns. Avoid cutting holes in the canopy larger than one tree height in diameter by distributing the cut over the entire area. In mixed stands, if the top story or rarely the first and second stories are pure pine, handle as a pure stand. If the top story is of mixed composition, cut as much of the basal area to be removed in pine as is possible and release the climax species, but do not cut all of the pine if it is needed to maintain the overstory.

   b. In pure or mixed stands with irregular stocking, an alternative first cut can remove about 40 percent of the basal area in a modified group selection. The group openings can be larger (2 to 3 times tree height) than in single-storied stands, but the area cutover should not exceed about one-third of the total. Openings should be irregular in shape without wind-catching indentations in the borders. This kind of cutting is not applicable in pure stands where mountain pine beetle or dwarf mistletoe impose limitations, because the interval between initial cutting and final harvest is likely to be too long to prevent serious mistletoe infection of new reproduction and/or loss of beetle-susceptible trees.

2. Moderate windfall risk situations

   a. The first cut should be an intermediate harvest that removes not more than 30 percent of the basal area on an individual tree basis. Predominants, and codominants and intermediates with long live crowns should be removed. Maintain the general level of the canopy by not cutting holes larger than one tree height in diameter in the canopy. Provision should be made to salvage blowdowns. Mixed stands should be handled as in low wind risk situations except that less basal area will be removed.

3. High windfall risk situations

   a. The choice is limited to either removing all the trees or leaving the stand uncut. Cleared openings can be up to about 5 acres interspersed with uncut areas. The cutover area should not exceed about one-third of the total.

MULTI – STORY

A. STAND DESCRIPTION

1. Usually broad-aged with a wide range in diameters.

2. If stands developed from relatively few individuals following disturbance, the overstory trees are coarse-limbed. Fill-in trees are better formed and finer limbed. Vigor of overstory trees varies from poor to good.

3. In stands that developed from deterioration of single- or two-storied stands, the overstory trees may be no limbier than the fill-in trees. Nearly all of the healthy, faster growing trees are below saw log size.

4. Stocking may be irregular.

5. May have a manageable stand of advanced reproduction.

6. In a mixed stand, the overstory may be pure pine or either pine, spruce and fir at higher elevations or pine and Douglas-fir at lower elevations. Understory trees have the same characteristics as pure stands except that the composition is likely to be species other than pine.

7. Stocking in mixed stands is more likely to be irregular.

8. Mixed stands frequently have a manageable stand of advanced reproduction of species other than pine.

B. SUGGESTED CUTTING PRACTICES

These are usually the most windfirm stands, even where they have developed from the deterioration of single- and two-storied stands. By the time they have reached their present condition, the remaining overstory trees are likely to be windfirm.

1. Low to moderate windfall risk situations

   a. There is considerable flexibility in harvesting these stands. All size classes can be cut with emphasis on either the largest or smallest trees in the stand. The first cut can range from an overwood removal to release the younger growing stock to a thinning from below to improve the spacing of the larger trees. Thereafter cutting can be directed toward either even-aged or uneven-aged management. In mixed stands the first cut should be an overwood removal of the pine to release the climax species. The understory trees should be thinned to improve spacing.

2. High windfall risk situations

   a. The safest first cut is an overwood removal with a light thinning from below to obtain a wider spaced, more open stand that can develop windfirmness. Thereafter, cutting can be directed toward either uneven- or even-aged management.

A. MODIFICATION OF SUGGESTED CUTTING PRACTICES IMPOSED BY DISEASE AND INSECT PROBLEMS

1. Dwarf mistletoe

a. Cut only in stands where the average mistletoe rating is 2 or less, (or less than about two-thirds of the trees are infected) and remove only the percentage of basal area recommended for the stand description and windfall situation. In single-storied stands, where site index is 70 or above, trees in the intermediate and lower crown classes should be removed in preference to dominants and codominants. If site index is below 70, trees in all crown classes are about equally susceptible to infection. In two- and three-storied, as much of the cut as possible should come from the second and third stories because these trees are likely to be more heavily infected than the top story. To minimize infection to new reproduction in single-, two- and three-storied stands, the final overstory removal should be made within 30 years after the regeneration cut when the average mistletoe rating is 1, and within 20 years when the rating is 2. Provision should be made to sanitize the young stand at the time of final harvest. In multi-storied stands, the safest procedure is an overwood removal with a cleaning and thinning from below.

b. In old-growth stands with an average mistletoe rating of greater than 2, any partial cutting, thinning or cleaning is likely to intensify the infection. The safest procedure, therefore, is to either remove all trees and start a new stand or leave the stand uncut. If the manager chooses to make a partial cut for any reason, the initial harvest should be heavy enough to be a regeneration cut. All residual trees must be removed within 10 years after the first cut, and provision made to sanitize the young stand at that time.

2. Comandra blister rust

a. Cut as many trees with stem cankers and spiketops as possible without removing more than the recommended basal area or cutting large openings in the canopy. Since the rate of spread in mature trees is relatively slow, and the disease is not transmitted from pine to pine, leaving a few infected trees is less of a risk than opening up the stand too much.

3. Mountain pine beetle

a. If the insect is present in the stand at an endemic level, or in adjacent stands in sufficient numbers to make successful attacks and:

(1) Less than the recommended percentage of basal area to be removed is in susceptible trees, any attacked tree and all of the most susceptible trees should be removed in the first cut. This will include most of the trees 14 inches d.b.h. and larger, and all trees 10 to 14 inches d.b.h. in vigor classes A and B. Provision should be made to salvage attacked trees, and a second cut should be made in about 10 years after the first cut.

(2) More than the recommended percentage of basal area to be removed is in susceptible trees, the manager has three options: (1) remove all the trees, (b) remove the recommended basal area in attacked and susceptible trees and accept the risk of future losses, or (c) leave the stand uncut. If the stand is partially cut or left uncut, some trees from 7 to 12 inches d.b.h. and most trees below 7 inches d.b.h. will survive all but epidemic outbreaks.

b. If the stand is presently sustaining an infestation that is building up, and the manager chooses to either partially cut or leave the stand uncut, he must accept the risk of an outbreak that could destroy most of the merchantable stand.

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MORPHOMETRY OF THREE SMALL WATERSHEDS, BLACK HILLS, SOUTH DAKOTA, AND SOME HYDROLOGIC IMPLICATIONS

by Teruo Yamamoto and Howard K. Orr

Abstract

Morphometry and hydrologic character of three small contiguous watersheds are analyzed in terms of elementary length dimensions, nondimensional expressions, and similitude concepts. The approach is based on theory that watershed morphology which evolves under the influence of dynamic processes should be consistently related to quantitative resultants of the processes. Within this framework, maximum length of master watershed and the average relief of first order basins scale most nearly the same as volume yield and stormflow peaks. It is theorized, therefore, that these form elements (1) exert primary control over or are closely related to volume yield and peak flows, and (2) are better indicators of relative volume yields and peak flows than is area on the surface of the laccolith. Different morphometric characteristics, however, may be controlling elements under conditions of different parent rock and climate. Dimensionless parameters such as shape are also examined.

Keywords: Hydrology, morphology, water yield.

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Morphometry of Three Small Watersheds, Black Hills, South Dakota, and Some Hydrologic Implications

by

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Morphometry of Three Small Watersheds, Black Hills, South Dakota, and Some Hydrologic Implications

Teruo Yamamoto and Howard K. Orr

Every watershed is unique. Its "uniqueess" may not be clearly evident, even to the racticed observer, but it in some way accounts r or is related to measurable differences in ydrologic behavior of contiguous and otherise macroscopically similar watersheds. orphometric (form) properties, for example, mprise a class of physical factors acknowlged as important in hydrologic behavior but hich are often difficult to apprehend, measure, press, or evaluate. Much of the qualitative storical effort in this field has been on a gional basis and has concentrated on evolun of landforms. However, quantitative ethods are by now so well established and cepted as to stimulate sporadic efforts to late morphometric properties to hydrologic erformance.

Such relationships have not been studied tensively on small forested watersheds. The resent study was undertaken in an initial tempt to identify significant morphometric arameters or classes of parameters and their ow implications. This kind of information sought not only as a means of improving ur understanding of basin morphology, water eld, and possible forest treatment response, ut also to establish a geomorphic benchmark on which to build further study and better nderstanding of the hydrologic functioning small forested watersheds in other geologic pes in the Black Hills.

The Study Watersheds

Three adjoining watersheds, 217, 89, and 0 acres, referred to as the Sturgis watershed, e being studied in detail. They are headwater ibutaries of Alkali Creek, which drains a rtion of the Vanocker Laccolith in the northstern Black Hills near Sturgis, South Dakota ig. 1). A number of such laccoliths, all of ertiary origin, are exposed at scattered locaons across the northern Black Hills.

The watersheds, numbered 1, 2, and 3 from st to west, all drain in a generally northerly rection (fig. 2). The watershed surfaces have en deeply dissected, apparently by the concentration of erosion along primary lines of weakness that developed during cooling of the igneous mass, and fractures that developed along these lines during subsequent erosional unloading.

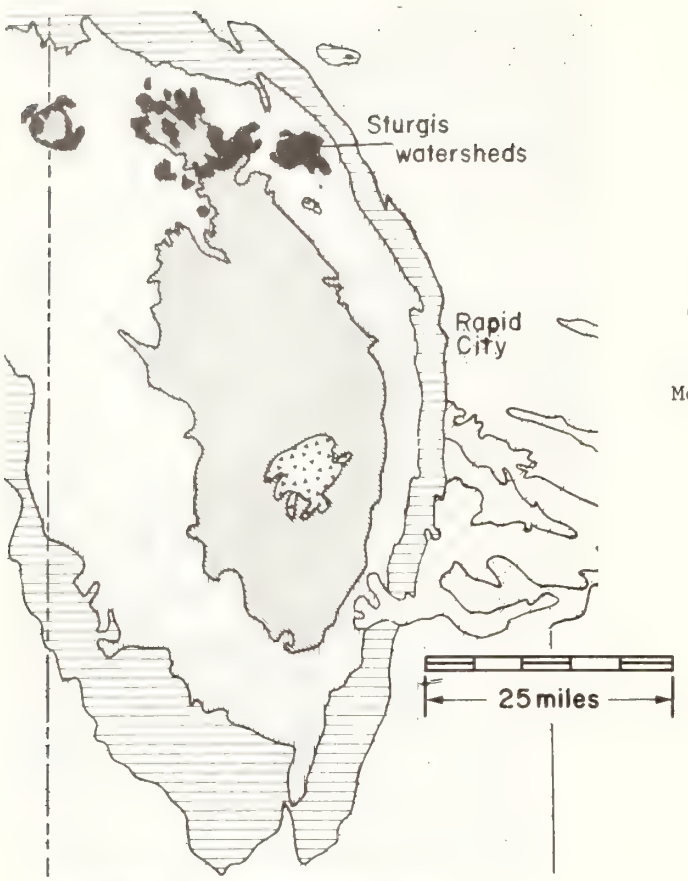
The parent rock is a hornblende-biotite quartz latite porphyry.[2] It is granitelike, dense, structurally firm, and practically impervious except in fracture and crushed zones. The most prominent and important feature of the basic rock structure is shallow sheeting, a form of rupture or cracking, parallel to the topographic surface. Sheeting decreases with increasing depth, where vertical jointing becomes a common feature.

Two distinctive kinds of soil are present in the watersheds — Gray Wooded soil and lithosol. The lithosols are shallow, lack B horizons or other clearly developed horizons, and consist of a weathered mass of hard rock or hard rock fragments and intermixed soil. These occupy approximately 47 percent of the total study area. The Gray Wooded soils (approximately 41 percent of total area) as described by Nishimura and Willmot[3] compare with published morphology (Radeke and Westin 1963). The most distinctive characteristics (from which the name is derived) is a well-developed A horizon of gray, very friable loam ranging from about 10 to 30 inches thick. The gray horizon grades into a brown B[2] horizon about 3 to 16 inches thick, ranging from clay to sandy-loam texture and granular to subangular blocky structure. This B horizon commonly terminates rather abruptly on the parent rock. Scattered areas of rock outcrop and rock slides occupy approximately 12 percent of the total area of all three watersheds.

All three watersheds are dominated by ponderosa pine forest. Because of many years of protection as a municipal water supply source,

[2] *Identified in detailed petrographic analysis of drill cores in 1969 by Professor Edward Bingler, formerly of the Geology Department, South Dakota School of Mines and Technology, Rapid City.*

[3] *Veteran Lookout Soils Report to Forest Supervisor, Black Hills National Forest, from Robert Gardner, Assistant Regional Forester, R-2 January 17, 1963, described by J. Nishimura and R. Willmot.*



LEGEND

Tertiary igneous intrusive rocks

Tertiary sedimentary rocks

Mesozoic rocks from Newcastle Sandstone (Lower Cretaceous) to top of Upper Cretaceo

Mesozoic rocks below Newcastle sandstone (Lo Cretaceous). Includes Spearfish Formation which is mainly Triassic but partly Permia

Paleozoic rocks

Precambrian granite

Precambrian metamorphic rocks

Figure 1. — Location of the Sturgis watersh

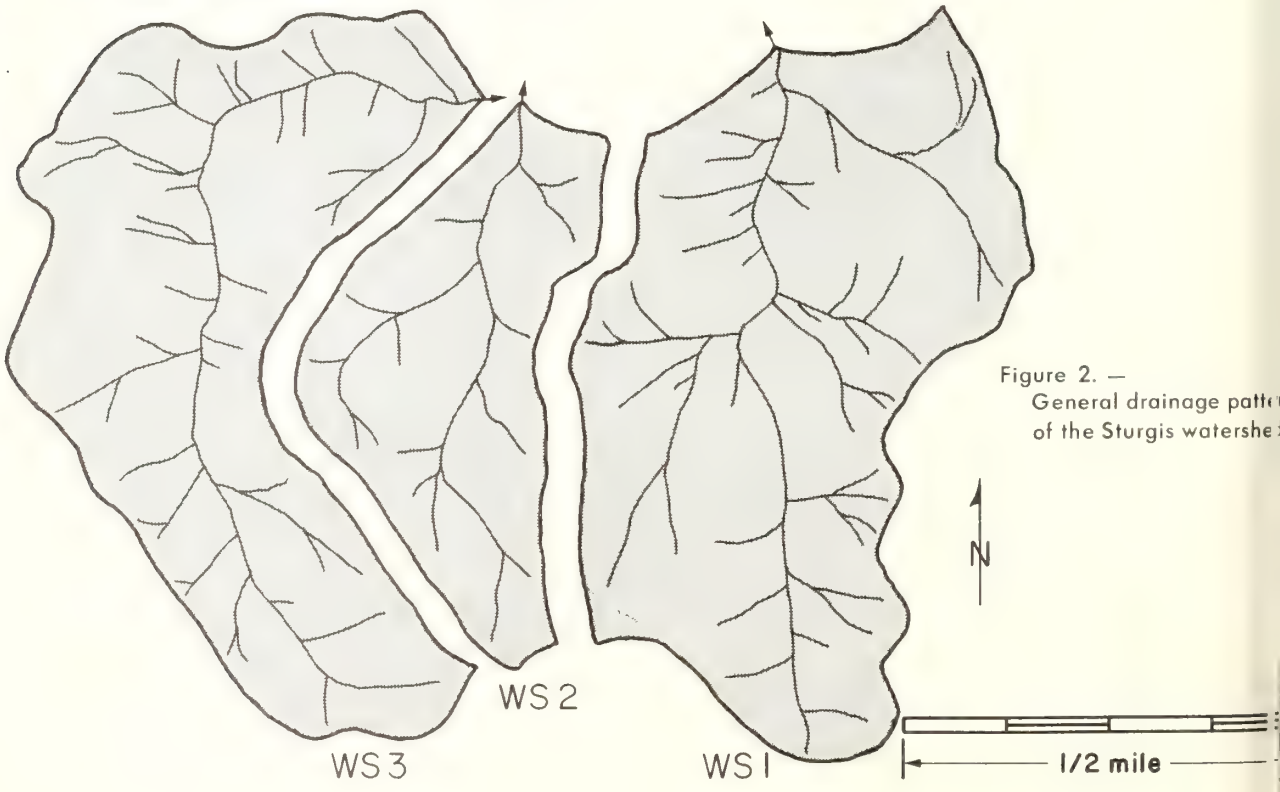


Figure 2. —
General drainage patt
of the Sturgis watershe

here is a greater than average amount f mature to overmature and decadent sawmber. However, second-growth pine (seedng-sapling to pole size) is present on 60 to 85 ercent of total area in different watersneds. scattering of white spruce, birch, aspen, and everal deciduous shrub species occur mainly ong channels. A variety of forbs and grasses re present, but production is relatively low ver much of the area due, at least in part, to he relatively dense forest canopy.

Runoff to the drainage channels is priarily subsurface through the shallow and ighly porous mantle. Infiltration capacity is eldom exceeded by local rainfall intensities. ittle evidence of overland runoff is visible. round water levels and streamflow stages repond quickly to spring and early summer recipitation and recede rapidly to low base ow levels.

Streamflow is continuously recorded at the outh of each watershed and precipitation is easured in a network of seven gages in the ree watersheds combined. Annual precipitaon has averaged 29.5 inches on all three atersheds through water year 1968.

Concepts and Methods

Horton (1945) proposed the theory that rainage basins develop in an orderly manner ccording to certain "laws" of drainage compotion. These laws are expressed quantitatively y relating the proportionality of number of reams, stream lengths, and slopes to "stream rder" (see section on Definitions and Derivaons). Morphometry of the three Sturgis waterheds is interpreted on the basis of the steady ate theory advocated by Strahler (1964) and ack (1960), an extension of Horton's theory. ccording to this theory, steady state is reached y continual adjustment of input (mainly preipitation) and output (flow and debris) until characteristic topographic form develops hich is quasi-time-independent. Continual reljustment of surface geometry must occur as e relief lowers, but takes place at an imperptibly slow rate, barring catastrophic events.

Scheidegger and Langbein (1966) present rther logical elaboration of this theory, acording to which an "ensemble" (which could a group of watersheds on a single parent ck type) contains samples of the changes that cur on a single watershed in time. It follows, en, that variation in space can be substituted r variation in time, and the rationale for tailed comparison of **individual** watersheds the following analyses is established. Differences between watersheds are then interpreted as more likely real than due to sampling or measurement error. These principles lead to a corollary theory that watershed form elements which evolve under the influence of dynamic processes should be consistently related to quantitative resultants of the processes.

The common expression of water yields and peaks (both are resultants of dynamic processes) on a per unit area basis (inches or acre-feet per square mile for yield and cubic feet per second per square mile (CSM) for peaks, as examples) is tacit admission of gross area control of output. It may at the same time be taken as indirect assertion that, input factors being the same, output should be strictly proportional to area. This is seldom the case, however. In a humid climate, for example, unit area yields tend to increase with area of small watersheds (Ogrosky and Mockus 1964). This observation is in agreement, at least directionally, with similitude concepts, which suggest that unit area depth of yield must increase in the same proportion as increase in square root of total watershed area.

Morphometric Measurement

A 1:24,000 U.S. Geological Survey Topographic map was enlarged to a scale of 1:3,600 for morphometric measurements. Streams were then systematically assigned to "orders." The smallest unbranched tributaries were designated first order, second order channel segments are formed by the union of two first order channel segments, and so forth, for successively higher orders (Strahler 1952). Form elements of the drainage net were then systematically measured with chartometer and planimeter; questionable interpretations were field checked and corrected as necessary. Three main groups of elements measured were: (1) length aspects of the watershed and the channel system, such as stream lengths, watershed perimeters, and watershed lengths; (2) area aspects of watersheds including basin areas, basin shapes, drainage density, and channel frequency; and (3) relief aspects of the surface such as channel gradient, ground slope, relief, and longitudinal profile. These elements are derived mainly from Horton's (1945) pioneering work and from the later contributions of Strahler (1958, 1964) and his colleagues.

Dimensional Analysis and Geometric Similarity

Concepts. — Dimensional expression and the application of simple principles of geometric similarity provide a useful means of analyzing

and comparing form and mechanical aspects of drainage basins not to be found in probability statistics — particularly when the number of sampled watersheds is small.

In the present case, three small contiguous watersheds are studied and compared in detail. For the most part, data are considered as whole-population statistics, subject only to measurement error. In this context, both the concept and application of morphometric analysis differs somewhat from the more usual approach which involves statistical inference.

Two watersheds are said to be geometrically similar when all corresponding linear elements of the two watersheds are in the same scale ratio (the same proportions) and when all corresponding angles and other dimensionless elements of the two systems have identical values (Strahler 1964). Scale ratios derived from average values have ordinarily been used in regional analyses. This approach has not apparently posed serious difficulties on such large scale because (1) a large enough number of watersheds are ordinarily included to minimize change of bias due to heterogeneous variances, and (2) master watersheds are within a narrow enough size range to mitigate the effect of size differences on scale comparisons of within-watershed elements. However, in our more restricted situation — small number and relatively small area of watersheds on a single geologic type — use of averages may have a different connotation. For example, in a strict prototype/scale model situation, the dimensions of first order basins in the larger prototype watershed should be proportionately larger than the corresponding dimensions of first order basins in a smaller, model watershed. In the real world, at least on the small scale we are presently considering, this is not a sound assumption. For example, on the same lithology under the same climate, the average of first order basin areas in similarly oriented watersheds would be expected to be about the same regardless of the size or order of the "master" or highest order watershed. (The same principle could apply also to higher orders.) On this basis it is theorized that **sum total** of first order basin areas may be as meaningful or more meaningful morphologically and hydrologically than **average** area.

Analytical Procedures. — All measured geometric elements (length, area, and volume) were reduced to root length dimensions (L) and dimensionless numbers (angles and ratios). Linear scale ratios [4] (conceptually the same as map scale) were calculated and used to co pare dimensions by size. That is, if two basi are geometrically similar, corresponding leng dimensions will all be in the same proporti — in other words, measures of correspondi dimensions of length (L), reciprocal of the verse of length (L^{-1}), square root of leng squared (L^{2} = area), and cube root of leng cubed (L^{3} = volume) will all have the sa ratio. Dimensionless numbers are used to cc pare form independent of size. Furthermo dimensionless properties such as angles a slope gradients of corresponding parts will equal. In nature, identical form values obvio ly cannot be expected, but close approxi tions, if existent, will be evident.

In analyzing hydrologic implications, it w theorized that those morphometric eleme which scale most nearly the same as **volu** of annual water yield, for example, should primary controls of or related to volume yi The study watersheds have all received pr tically the same "depths" of precipitation put each year. This is the entry point systems in which component elements influe the distribution or routing of input, and cor quently control or influence the volume out in some way. In this process we have assur that basin characteristics other than geome are essentially similar, or are themselves lated to geometry in some consistent and ical manner. Subsequent analyses will be aim at identification and explanation of signific interactions which could involve a variet other factors including input (precipitation other external atmospheric variables), fo and other plant cover, and soil and bedr

Throughout the following discussion, s ratios are presented as WS1/WS2, WS3/W and WS1/WS3 (WS = watershed), in line the previously stated large area/small (prototype/model) specification.

Results

Watershed Areas and Yields

The study watersheds differ (are uniq first of all, in terms of gross area (tabl Total annual water yields (volume), as pected, rank in the same order.

In comparing WS1/WS3, scale ratios o yields are very nearly the same as scale r of areas of both the average and sum total first order basins and also master orders (t 2), and are consistent year to year. Howe in the two other comparisons, (WS1/WS2 WS3/WS2), the scale ratios of gross vol yield are smaller than the scale ratios of

[4] *Ratio value of the larger to the smaller basin is specified.*

Table 1.--Annual precipitation and water yield, Sturgis watershed

Water year	WS1 (217 acres)			WS2 (89 acres)			WS3 (190 acres)		
	Precipitation	Yield		Precipitation	Yield		Precipitation	Yield	
	Inches	Acre-feet	Inches	Inches	Acre-feet	Inches	Inches	Acre-feet	Inches
1964	31.5	118.08	6.54	32.4	53.47	7.21	31.8	100.07	6.26
1965	34.8	232.37	12.85	34.3	100.35	13.53	34.7	189.05	11.88
1966	24.8	69.44	3.84	24.0	29.82	4.02	24.4	52.57	3.32
1967	32.4	258.23	14.28	31.8	107.77	14.53	32.3	195.70	12.36
1968	24.5	35.26	1.95	24.1	17.06	2.31	24.6	28.18	1.78
Average	29.60	[1]142.68	7.89	29.32	[1]61.70	8.32	29.56	113.11	7.12

[1] Used in illustration of scale ratio in footnote 2, table 2.

Table 2.--Watershed areas (horizontal projection), and scale ratios (λ) of watershed areas, water yields, and stormflow peaks (average of 21 events), water years 1964-68

Watersheds	Area		Scale ratios, λ					
	First order average	Master order	Watersheds	Area			Average yield[2]	Peak flow[3]
				First order average[1]	First order total	Master order		
	- - - - Acres - - -							
WS1	2.84	217	WS1/WS2	1.01	1.69	1.56	1.31	1.29
WS2	2.80	89	WS3/WS2	.97	1.63	1.46	1.22	1.28
WS3	2.71	190	WS1/WS3	1.05	1.04	1.07	1.08	1.01

[1] For example, $\sqrt{\frac{2.84}{2.80}} = 1.01$

[2] For example, $\sqrt[3]{\frac{142.68}{61.70}} = 1.31$ (data from table 1)

[3] $\sqrt[3]{\frac{cfs}{cfs}} = 1.29$

otal areas of first order basins and areas of the naster orders (total watershed). In other words, VS1 and WS3 both yield somewhat less water or their size than WS2. Order one average reas are so nearly the same (near 1:1 scale) in ll three comparisons that it does not appear hey could have a significant independent influence on yield.

The difference in yields from WS1 and WS3 ompared with WS2 is also evident in terms of nit area yields (inches) (table 1) which are onsistently and significantly ($P < .05$) less from oth WS1 and WS3. This is a contradiction of he previously cited statement of theory that vater yield per unit area increases with increasng watershed area. The WS1/WS3 comparison s borderline significance. ($.1 < P < .05$).

Average stormflow peaks as well as annual yields rank in the same order as entire watershed (master order) areas, and also scale very nearly the same as annual yields (table 2). WS1 and WS3 peaks scale to WS2 in almost exactly the same ratio. Consequently the WS1 WS3 scale ratio is almost exactly 1:1, and the scale ratios are different than for area.

The different area and yield scale ratios in both the WS1/WS2 and WS3 WS2 comparisons definitely suggest that other elements besides area also influence or at least partially control the volume yields and peak flows. On the other hand, the nearly 1:1 scale ratios in the WS1 WS3 comparison still suggest primary area control. Now the main questions are "What elements, if any, scale more nearly the same as

yield and peak flows than do areas in the WS1/WS2 and WS3/WS2 comparisons?", and "Are ratios of other elements consistent with the similitude indicated by closeness of the area and yield scale ratios in WS1 versus WS3?" Similar questions are pertinent regarding constancy of nondimensional elements.

Linear Aspects of Drainage Basin and Channel System

Dimensional Elements.—In terms of linear elements listed in table 3, WS1 and WS3 scale about the same as they do in terms of area and yield, including order one average, order one total, and master order (total watershed) — with one outstanding exception: the trunk channel mesh length, master order. WS3, though smaller in area, is larger than WS1 in terms of master channel trunk length but smaller in terms of water yield.

Order one elements are included in the preceding section and in tables 2 and 3 because of evidence that the character of entire watersheds of hierarchy greater than order one is in real sense controlled by or is related to character of contained first order basins (Morisawa 1962). Except for master channel mesh length, the consistency of tabulated scale ratios in the WS1/WS3 comparison thus far supports this contention.

However, little consistency is apparent in either the WS1/WS2 or WS3/WS2 ratios, nor are both of any pair of ratios in table 3 consistent with yield ratios **except for maximum basin length**. On the other hand, the near 1:1 ratios of order one averages again indicate relatively close similarity of order one basi among watersheds. Hence, planimetric par meters of order one averages cannot possib explain differences in yield scale. However, i terms of sum total area of order one, WS1 ar WS3 are even larger in relation to WS2 th they are in terms of area of master order (tab 2). This scale difference is also obvious in ord one sum-total-area proportion of master ord areas which are 55, 47, and 59 percent for WS WS2, and WS3, respectively. All other ar (interbasin area) drains directly into seco or higher order channels where conveyan loss very likely is less.

The almost exact correspondence of t scale ratios of maximum length of the mast watersheds with yield and peak flow scale rati is accepted as evidence that maximum leng is a primary control element in both yield a peak flow. The other listed elements, includi area, are seemingly less effective.

Dimensionless Elements.—The weight mean **bifurcation ratios** of WS1, WS2, and WS respectively, are 3.43. 4.64, and 5.15. The val of 3.43 means that, on the average, there a 3.43 times more channels of any given orc than of the next higher order. According Strahler (1964) bifurcation ratios between 3 a 5 are characteristics of basins not having d torted geologic structure. The borderline val for WS3 suggests possible structural distorti which may account for certain scale distortio The above values in general are similar to or reported by Melton (1957) for basins of simi lithology in New Mexico, Arizona, Utah, a Colorado.

Table 3.--Average values (L) and scale ratios (λ) of horizontal linear elements of drainage basi and their channel systems

Watersheds	Trunk channel (mesh length)		Maximum basin length (ML)		Maximum basin width (MW)		Basin perimeter (P)	
	First order average	Master order	First order average	Master order	First order average	Master order	First order average	Mast orc
	Feet							
WS1	574	4,926	625	4,665	276	2,775	1,486	13,7
WS2	482	3,435	639	3,562	295	1,545	1,583	8,7
WS3	524	6,450	599	4,230	282	2,370	1,453	14,2
	Scale ratios λ							
WS1/WS2	1.19	1.43	0.98	1.31	0.94	1.80	0.97	1.
WS3/WS2	1.09	1.88	.94	1.19	.96	1.53	.94	1
WS1/WS3	1.10	.76	1.04	1.10	.98	1.17	1.02	

Generally speaking, **axil angles**, the upper ngle of entry of a channel into a channel of ext higher order, are similar in all three water- neds. For order one entry into order two, the verage angles are 50, 52, and 52 degrees re- pectively for WS1, WS2, and WS3. These acute ngles are to be expected, considering the rela- ve steepness of the watersheds. Entry tends nore toward right angles on gentler slopes and pward even more acute angles on steeper opes.

Basin Azimuth.—The azimuth of basin di- meter (downstream direction) for all orders, nd associated average ground slopes were lotted on polar coordinate paper. These lottings showed that the majority of compo- ent basins in all three watersheds face north. 'S3 has the most distinctive pattern of azimuth ersus slope distribution. No basins face south west, a concentration of the steeper slopes ce east, and concentrations of the gentler opes face northeast and northwest. WS2 has o basins facing southeast to west. WS1 has the ost even distribution in full azimuth, but here o the heaviest concentration faces generally orth.

rea Aspects of Drainage Basins

Dimensional Elements.—Gross areas and e area scale ratios have already been pre- nted in table 2. Other well-known area aspects drainage basins are drainage density (miles channel per square mile of area, dimension- ly equal to L^{-1}), the constant of channel aintenance (square feet of watershed area per ot of channel length, dimensionally equal to L, and the inverse of drainage density), and channel segment frequency (number per square mile, dimensionally equal to L^{-2}). Computed values and scale ratios are shown in table 4. Again the WS1/WS3 scale ratios are the most consistent with scale ratios already presented (yield, area, and linear dimensions), but still there is enough discrepancy to suggest distortion. WS1 has slightly less length of channel per unit of watershed area (or more area per unit of channel length) than WS3, and slightly less than indicated by area and yield scale ratios. Channel segment frequency is almost exactly the same on the two watersheds which also indicates distortion. WS1 would have to have fewer channel segments per unit area for the scale ratios to be consistent with those for area and yield, or conversely, WS3 would have to have a greater number of channel segments per unit of area.

It is again in the scale ratios involving comparison of WS2 with WS1 and WS3 that distortions from both volume yield and area ratios are most pronounced. The near 1:1 or smaller scale ratios in the WS1/WS2 comparison indicate that WS2 has about the same or just slightly fewer miles of channel per square mile of area than WS1 (drainage density), about the same or slightly more area per foot length of channel (constant of channel maintenance), and about the same to a slightly smaller number of channel segments per square mile of area (channel segment frequency). The same contrasts are present in comparing WS3 with WS2, except that they are even more pronounced. Thus, WS2 draining the smallest area has a less finely dissected drainage network than either of the larger watersheds.

Table 4.--Area elements of the watersheds and their scale ratios (λ)

atersheds	Drainage density		Constant of channel maintenance		Channel segment frequency	
	First order[1]	Master order	First order	Master order	First order	Master order
	Mi/sq mi		Sq ft/ft		No/sq mi	
WS1	13.21	13.41	400	394	225	174
WS2	13.38	13.09	395	403	229	137
WS3	14.91	14.98	354	352	236	175
	Scale ratios λ					
WS1/WS2	1.01	0.98	1.01	0.98	1.01	0.89
WS3/WS2	.90	.87	.90	.87	.98	.88
WS1/WS3	1.13	1.12	1.13	1.12	1.02	1.00

[1] First order values computed from totals of first order areas and channel lengths rather than from averages.

Dimensionless Elements (Shape).—Several of the most commonly used shape elements are presented in table 5. The "lemniscate" is perhaps the most realistic because its somewhat "pear" or "teardrop" shape more frequently approximates real watershed shapes than other measures such as the circle (Chorley et al. 1957). However, some common attributes are apparent.

The length and area of a watershed are combined to calculate the "lemniscate constant" which defines basic length/width proportions of a perfect lemniscate having the same area and same length as the watershed (see section on Definitions and Derivations).

The larger the constant the more elongate the outline. A value of unity indicates a circle. The lemniscate ratio then indicates how closely the actual watershed shape approaches the perfect lemniscate. A ratio of unity would indicate perfect correspondence.

As shown in table 5, the order one constants indicate relatively elongated lemniscates, and the ratios indicate relatively close approach to the perfect lemniscate shape in all three watersheds. In master order (entire watersheds), the constants indicate a more rotund shape for WS1 and WS3 but still a fairly elongate shape for WS2. The WS2 lemniscate ratio indicates closest correspondence with the perfect shape. More discrepancy is present in the other watersheds — particularly WS3. Shape distortion of WS3 is clearly visible in figure 2.

A general consistency of individual order one shape elements among watersheds further strengthens the evidence of their similarity.

The most outstanding and consistent feature of master watersheds is the greater relative elongation of WS2 than the other watersheds. The marked exceptions involve WS3, which most poorly fits the lemniscate shape as indicated by the constants. WS3 is also least circular and most elongate when master channel mesh length is used in place of maximum basin length. The shape elements also support the possibility of geologic distortion of WS3 (perhaps through difference in jointing of igneous mass) as interpreted from the higher bifurcation ratios pointed out previously.

Relief Aspects of Drainage Basins

Relief is of fundamental importance because of its critical role in watershed dynamics particularly in velocity and the resulting eroding power of flowing water. The concept of relief is easily visualized and understood, but measurement and expression of the relief of complex watershed forms in terms that can be related to hydraulic or hydrologic performance is problematical. Depending on intended use, relief is expressed either in terms of absolute vertical rise (dimensionally equal to L) or vertical rise per unit of some horizontal length dimension (a dimensionless ratio).

Dimensional.—Relief of geometrically similar watersheds should be in the same proportions as horizontal linear elements. Relief can be expressed in many ways, ranging from maximum basin relief to rise along the trunk channel from the watershed mouth to the watershed divide. The latter property may not be appropriate for oddly shaped basins or basins with the highest point at some place other than the point farthest removed along

Table 5.--Dimensionless area elements (shape) of the study watersheds

Dimensionless area elements	Watershed 1		Watershed 2		Watershed	
	First order	Master order	First order	Master order	First order	Mas ord
Leminscate constant	2.48	1.81	2.63	[1]2.57	2.39	[1]
Leminscate ratio	.97	.85	.95	.93	.96	[2]
Elongation ratio, using average--						
Maximum length and area	.64	.74	.62	[1] .62	.65	
Trunk channel mesh length and area	.69	.70	[3] .82	.65	.74	[1]
Circularity ratio	.70	.63	.65	.63	.70	[4]
Maximum length/maximum width, using averages	2.26	1.68	2.17	[1]2.31	2.12	
Area/maximum length squared, using averages	.32	.43	.30	[1] .31	.33	

[1]Most elongate, master order.
[2]Poorest fit, master order.
[3]Least elongate, first order.
[4]Least circular, master order.

Table 6.--Dimensional aspects of basin relief

atersheds	Rise along trunk channel (mesh length)		Rise along maximum basin length (ML)		Rise from lowest point on basin perimeter (maximum basin relief, H)	
	First order average	Master order	First order average	Master order	First order average	Master order
	Feet					
WS1	189	535	207	539	217	710
WS2	145	521	174	573	180	580
WS3	165	555	191	508	200	623
	Scale ratios [1]					
WS1/WS2	1.30	1.03	1.19	0.94	1.20	1.22
WS3/WS2	1.14	1.07	1.10	.89	1.11	1.07
WS1/WS3	1.14	.96	1.08	1.06	1.08	1.14

ainage line from the mouth. Values and scale tios of three measures of relief in the Sturgis atershed are presented in table 6.

The foregoing general consistency of WS1/S3 linear scale is preserved in both first order erages and in master order. However, in-easing distortions are evident in the WS1/S2 and WS3/WS2 comparisons. For example, e ratios of order one averages in all classes elements thus far considered have indicated latively close similarity of order one basins nong the three watersheds. Now, in the case relief, there is strong suggestion of scale tios consistently greater than unity. In fact, e ratios approach the yield scale ratios. Con-rsely, the master order scale ratios are nearer ity.

Dimensionless.—Three primary relief properties are measured in dimensionless terms — channels, valley side slopes, and interrelations of these two which reduce basically to area-mean-slopes. Typical values are presented in table 7.

First order channels average a slightly gentler gradient in WS2 than in WS1 or WS3; WS3 is second, and WS1 first order gradients are steepest. Average ground slopes of first order basins occur in the same sequence and have practically the same values. Slope ratio, which combines these two factors, indicates slightly steeper average channel gradient than ground slope in WS2. The difference probably is not significant, however, and the ratio is probably not significantly different from those

Table 7.--Dimensionless relief properties of the Sturgis watershed

Dimensionless relief properties	Watershed 1		Watershed 2		Watershed 3	
	First order	Master order	First order	Master order	First order	Master order
runk channel gradient mesh length (percent)	32.9	10.9	30.0	15.2	31.5	8.6
asin maximum length relief ratio	.33	.12	.27	.16	.32	.12
elative relief (basin ML relief ÷ perimeter)	.14	.039	.11	.065	.13	.036
alley side slope (percent)	42.2	53.2	40.6	50.1	38.9	42.7
verage ground slope (percent)	33.6	37.8	29.3	36.4	31.7	34.3
lope ratio (channel gradient, mesh length ÷ average ground slope)	.98	.29	1.02	.42	.99	.25
uggedness number (DD x MH ÷ 5280)	.62	1.80	.49	1.44	.68	1.78

for WS1 or WS3, which are practically identical in the first order.

An opposite trend is apparent in master order trunk channel gradient (mesh length). WS2 is the steepest, which is reflected in the slope ratio. Values of master order slope ratios are also lower than those of first order. This means that master channels become less steep downstream, while average ground slope actually increases. Relative change is less in WS2 than in WS1 or WS3. Hence, the slope ratio is highest in WS2. "Ruggedness numbers" indicate a similar trend. Where there is the greatest contrast between channel gradient and mean ground slope (lowest slope ratio) ruggedness number is highest. Thus, WS1 and WS3 are "more rugged" than WS2. It so happens that, since drainage densities remain nearly the same with increasing order, ruggedness is in the same order as maximum relief, and indicates increasing slope steepness downstream in all three watersheds. Similar relationships are evident in valley side slope. WS1 is steepest, WS2 intermediate, and WS3 the gentlest sloping in both first and master order. In all three cases, side slopes become steeper downstream (master order). Contrast is least in WS3.

In summary, WS2, which yields the most water per unit area and which yields proportionately more than might be expected from area scale ratios, has:

1. More gently sloping order one channels (mesh length).
2. Gentlest average ground slope in order one.
3. Steepest master channel (mesh length).
4. Largest slope ratio (least difference between average ground slope and master channel gradient) consequently is least rugged both in first order and master order.

WS1, on the other hand, has:
1. Steepest first order channels.
2. Steepest valley side slopes, both first order and master order.
3. Slightly steepest average ground slope, both first order and master order.

WS3 has:
1. Gentlest master channel slopes.
2. Gentlest valley side slopes, both first order and master order.
3. Lowest average ground slope of master watershed.

Slope distributions (from hypsometric analyses) lead to similar conclusions. These analyses indicated, for example, that 47, 36, and 20 percent of the areas of WS1, WS2, and WS3, respectively, have slopes steeper than 40 percent. The differences here are of greater relative magnitude than differences in average ground slope of the master watersheds, though in the same sequence.

Hypsometric Function

Percentage hypsometric curves, which are graphs of the continuous function relating relative height to relative area of the entire watersheds, are shown in figure 3. The first-order—master order percentage integrals for WS1, WS2, and WS3, respectively, are: 53.8—55.5; 57.0—54.3; and 53.9—55.7. These values indicate almost identical percentages of the reference volumes of the total basins remaining. Hence, it may be concluded that the overall erosion and degradation process has been closely similar on all three watersheds.

Despite the close similarity indicated by the integrals, there are differences in distribution. The curves in figure 3 indicate, for example, that WS1 has approximately 72 percent of its horizontal area above median elevation, compared with 60 and 57 percent for WS2 and WS3. This is in line with the higher percentage of slopes steeper than 40 percent in WS1 than in WS2 and WS3, the steeper average ground slope of WS1, and the increasing ruggedness downstream.

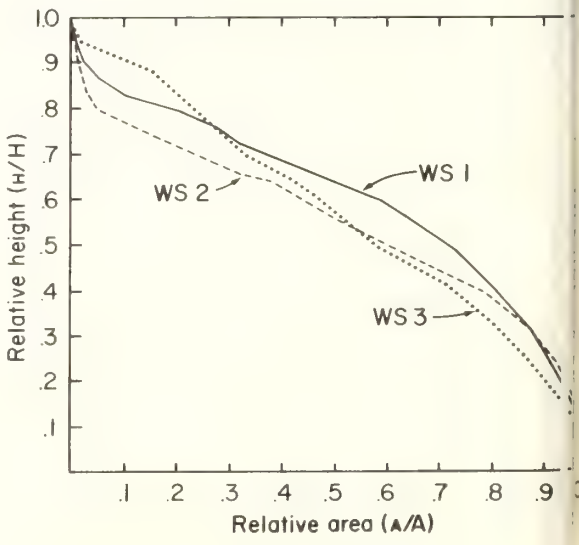


Figure 3. — Percentage hypsometric curves (area-elevation distribution), Sturgis watersheds.

ongitudinal Profiles of Principal Channel

If the hypsometric integrals and curves e accepted as indices of steady-state drainage asins, then the longitudinal channel profiles present graded streams or profiles of equilibum. The graded stream has been taken to ean that the stream has just that slope which rovides the competency and capacity to transort its load. In these adjoining basins where lief is similar, WS2 with its shortest stream ngth (horizontal map projection) has the eepest stream gradient. The weighted stream radients (Taylor and Schwarz 1952) as shown figure 4 indicate relatively straight profiles. enerally a graded stream is said to have a nooth, concave longitudinal profile, but convity alone is not a reliable index to equilibum. The straight profiles reflect relatively niform rock control and minor deposition ong the channels. Downcutting is negligible these drainages, and lateral expansion is ominant.

Discussion—Summary

This paper reports detailed form (morphoetric) comparisons of three small, contiguous atersheds. All three are on one of the granite-e early Tertiary intrusions that dot the rthern Black Hills. Ponderosa pine forest minates the entire area. Specification of orphometric elements is based on principles t forth by Horton (1945) and elaborated by ahler (1958, 1964) and his associates. The watersheds are assumed to be in "steady state" (input-output equilibrium) which is quasi-time-independent (Strahler 1964). The study watersheds and their component subbasins of all orders are also assumed to be an "ensemble" whose variation in space is a reflection of possible variation in time on a single water shed (Scheidegger and Langbein 1966). This is the rationale upon which the detailed comparisons of the watersheds are based.

In a macroscopic sense, it must be concluded that the watersheds are alike since they are contiguous, are oriented about the same, all have the same type of bedrock, and all are subject to the same climatic environment. In the absence of further detail, it would be appropriate to consider water yield, for example, only in terms of averages for the ensemble. But where other theoretically relevant details such as morphometric variations are available or are derived, it is postulated that they can be related to variations in hydrologic response within the ensemble.

The three study watersheds differ in gross area, gross water yield, and peak stormflows. Applying concepts of dimensional analysis and geometric similitude, and calculating scale ratios, it is obvious that the watersheds are also geometrically dissimilar. Greatest scale dissimilarity (or distortion) is evident in comparison of the two largest with the smallest watershed.

It is postulated that dimensional elements having scale ratios most nearly the same as water yield are best related to or control yield, despite extreme distortion in other respects.

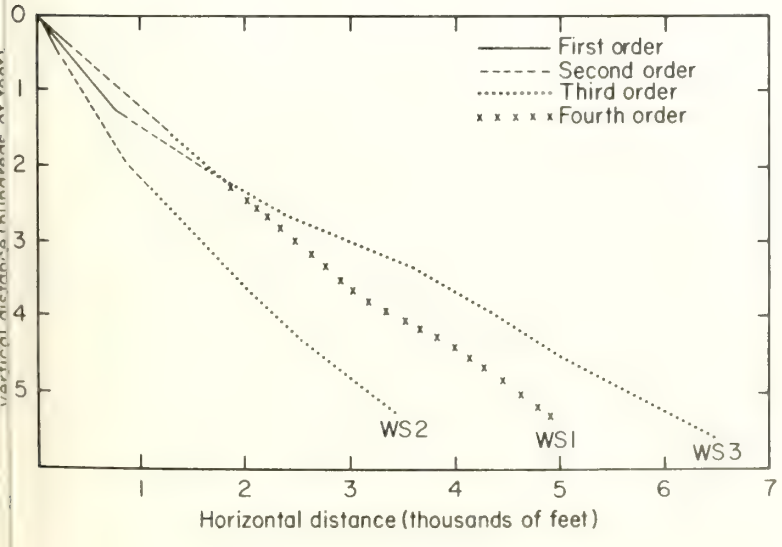


Figure 4. — Longitudinal profiles of the master channels of the Sturgis watersheds.

The "most probable" relationships based on this postulate can be seen in the graphical summary of scale ratios in figure 5.

In the WS1/WS2 comparison, two elements scale almost exactly the same as yield — maximum length of the master basin and average relief of first order channels (mesh length). The same two elements also scale most nearly the same as yields and peaks in the WS3/WS2 comparison. Other elements that scale closely enough with yield and peak flows in both comparisons to suggest some possible but lesser degree of control include average mesh length of first order channels, total rise along maximum length of first order basins, and maximum relief of both first order and master basins.

In the WS1/WS3 comparisons, the same elements scale with yield and peak flows as in the WS1/WS2 and WS3/WS2 comparisons — plus practically all of the other dimensional elements except for master channel mesh length. In this respect WS3 scales substantially larger than WS1. WS3 also scales slightly larger than WS1 in terms of perimeter of master order basin and master channel relief (mesh length), but the distortion is less obvious. The similarity of first order average area and horizontal linear characteristics among watersheds is apparent in the clustering of scale ratios close to the 1:1 (1.0) level in all three comparisons. However, there is a definite departure from unity scale in first order relief elements, which suggests at least partial control of yield and peak flow.

Average shapes of first order basins are also similar among all three master watersheds. Moderate to close similarity is indicated in four of the seven computed indices. However, there is a definite difference among the master watersheds. WS2 with its more regular outline is the most elongate, relatively, but WS3 shape is definitely distorted. This was suggested in the greater master channel mesh length and perimeter in WS3 than in WS1, and is confirmed by the shape indices. There is nothing particularly distinctive about shape in WS1 except that there is an apparent tendency for first order basins, as is also the case in both WS2 and WS3, to be more elongate than the master order.

Dimensional elements of maximum length of master basin and average rise from channel mouth to basin divide of first order basins exert the greatest apparent control over yield and peaks. The combination of length and rise expresses slope gradient as a dimension

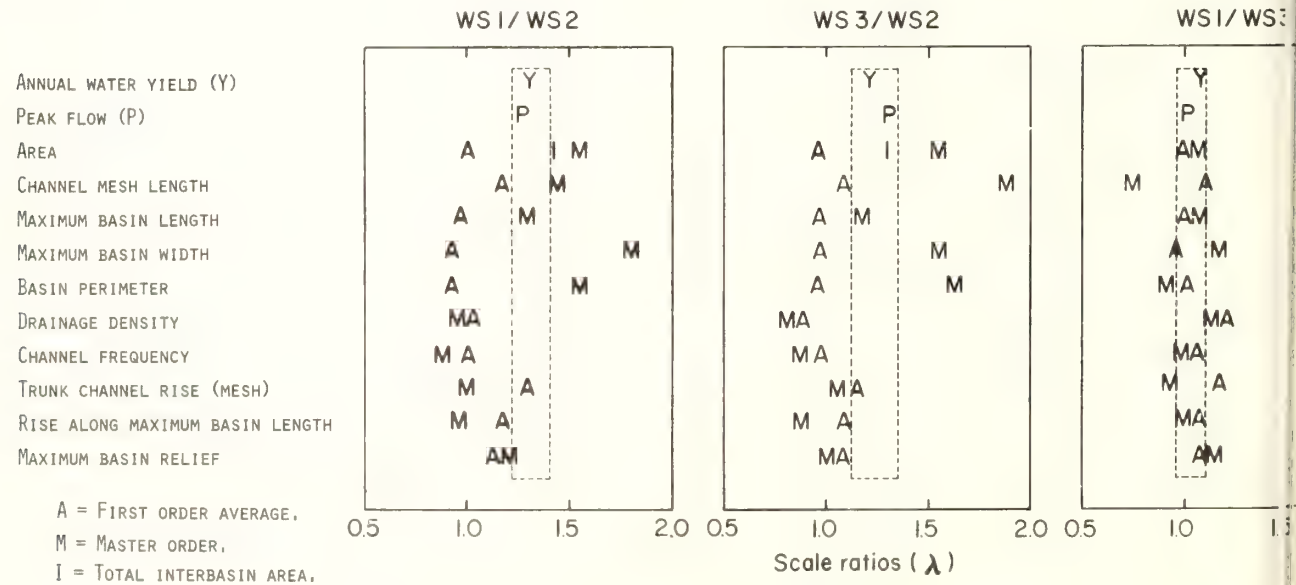


Figure 5. — Scale ratios of linear dimensions of the Sturgis watersheds. It is postulated that those elements most nearly in vertical alinement with Y and P (yield and peak flow scale ratios) are most closely associated with and hence are primary controls of Y and P.

umber. Computed values indicate WS2 has the ost gently sloping first order channels but ie steepest main channel. WS1, on the other and, has the steepest valley side slopes in oth first order and master order, and also ie steepest average ground slope in both first rder and master order. WS3 has the most ently sloping master channel, valley side opes (both first and master order), and average round slope (master order). The contrasts in elief are further emphasized in slope distribu- on analysis, which indicates that 47, 36, and) percent, respectively, of the total areas of 'S1, WS2, and WS3 have slopes steeper than) percent.

Indications are that, within the restricted ope of this study — on one rock type, and nder spatially uniform climate — maximum ngth of master watershed and relief of the ntained first order basins are more meaning- l indicators of relative yield and stormflow aks than is gross area. WS2, the smallest area the three, is relatively the most elongate d has the most gently sloping first order annels linked to the steepest master channel. S2 also has the smallest percentage of total ea in the first order basins, which means at a larger percentage of total area nterbasin) drains directly into second or higher der channels, on or near bedrock, where annel transmission loss should be minimum. his may be one of the important reasons why S2 has a higher relative yield than either WS1 WS3.

This study has produced some insights re- arding the relative importance of a variety morphometric elements to volume of water eld and storm peak discharges. Interpreta- ons need to be further tested by extension to her watersheds of the same geologic type and to other geologic types. Concurrent studies e needed on the influences and interactions other factors, especially soil and rock mantle haracteristics and their distribution.

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Stream or channel: (used interchangeably) — drainageway.

Stream order: Level of succession in joining of tributaries within a drainage network. Strahler's (1952) method designates the smallest unbranched tributaries as first order. Confluence of two streams of the same order forms a stream of next higher order.

Trunk stream: Extension of channel of any order in an upstream direction through the hierarchy to and including first order. Extension is based on rules established by Horton (1945) as follows: (a) starting below any junction, a straight line is extended upstream through the bifurcation; (b) the stream joining at the lesser angle is designated the trunk stream; (c) if junction angles are about the same, the longer stream is taken as the trunk stream or trunk channel.

Stream segment: Any complete single stretch of stream or channel of any given order. A first order stream or channel segment terminates where an incised channel is no longer visible.

Mesh length: Straight line extension of stream length to the basin divide (dimension L).

Master watershed: Entire watershed (complete hierarchy).

Master channel: Trunk channel of the master watershed.

Maximum basin length (ML): Horizontal straight-line distance from watershed mouth to most distant point on the watershed divide (dimension L).

Maximum basin width (MW): Maximum width normal to ML (dimension L).

Basin diameter: Horizontal straight-line distance from basin mouth approximately parallel (in line) with master channel to watershed divide. Criteria given by Maxwell (1960) aid in reproducibility (dimension L).

Basin perimeter: Horizontal distance around the periphery (dimension L).

Bifurcation ratio: Ratio of the number (N) of basins of order u to number of streams of next higher order (dimensionless).

Basin azimuth: Degrees of arc in a horizontal angle measured clockwise from true north to the mouth direction of the basin diameter (dimensionless).

Axil angle: Term denoting angle of junction of tributaries or entrance angle. It is the upper angle between the main channel and a branch (dimensionless).

Basin area: Acres of square miles, horizontal projection (dimension L^2).

Drainage density: Total length (miles) of a streams of all orders in a watershed pe unit of horizontal area (square mile) (dimension L^{-1}).

Constant of channel maintenance: Horizontal area, square feet, per foot length of channel (inverse of drainage density) (dimension L).

Stream frequency: Number of stream segments per square mile of watershed area (dimension L^{-2}).

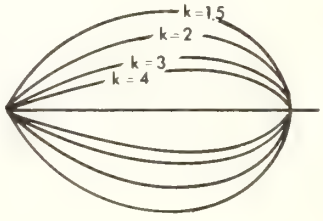
Circularity ratio: Ratio of the area of a basi to the area of a circle having the same perimeter as the basin. The closer the ratio approaches unity the more circular the shape (dimensionless).

Elongation ratio: Ratio of the diameter of a circle having the same area as the basin to basin diameter. The smaller the ratio the more elongate the shape (dimensionless).

ML/MW: Ratio of maximum basin length to maximum basin width (dimensionless).

A/ML^2: Ratio of basin area to the square of maximum basin length (dimensionless).

Lemniscate constant (k): $k = 1^2 \Pi/4A$ where 1 is the maximum basin length (ML) and A is basin area. The constant k expresses the relationship between the maximum length and maximum width of the loop of a lemniscate, as illustrated below. (After Chorley et al. 1957).



The loop is circular when the constant is unity (dimensionless).

Lemniscate ratio: Ratio of the perimeter of the lemniscate shape indicated by k to the actual drainage basin perimeter. The closer the lemniscate ratio approaches unity the nearer the basin shape approaches that of the pure lemniscate (dimensionless).

Rise or relief (used interchangeably): Increase in elevation, usually in feet (dimension L).

Maximum basin relief: Rise from lowest to highest point on the basin perimeter (dimension L).

pe or gradient: Rise per unit of horizontal distance, a ratio, usually expressed in percent (dimensionless).

sin ML relief ratio: Ratio of rise along ML to ML (dimensionless).

lative relief: Ratio of rise along ML to basin perimeter. Perimeter as the denominator permits characterization of oddly shaped basins where highest relief is located away from the point opposite the basin mouth (dimensionless).

lley side slope: Gradient of valley sides leading directly to stream channels, measured normal to contour (dimensionless).

erage ground slope: Total length of contours multiplied by contour interval and divided by basin area (dimensionless).

pe ratio: Ratio of channel gradient (mesh length) to average ground slope (dimensionless). It is a measure of the horizontal angle that the lateral slope makes relative to the channel slope. A low slope ratio indicates that the lateral inflow tends to enter the streams at right angles, whereas the angle of inflow becomes more acute as channel slope approaches ground slope. The slope ratio tends to decrease with increase in drainage area.

Ruggedness number: Drainage density multiplied by maximum basin relief and divided by 5,280 (after Strahler 1958). The larger the number the more rugged.

Percentage hypsometric curve: The plot of a continuous function relating relative height to relative area.

Hypsometric integral: The relative area below the hypsometric curve (dimensionless).

Yamamoto, Teruo, and Howard K. Orr.
1972. Morphometry of three small watersheds, Black Hills, South Dakota, and some hydrologic implications. USDA Forest Serv. Res. Pap. RM-93, 15 p. Rocky Mt. Forest and Range Exp. Stn., Fort Collins, Colo. 80521.

Morphometry and hydrologic character of three small contiguous watersheds are analyzed in terms of elementary length dimensions, nondimensional expressions, and similitude concepts. The approach is based on theory that watershed morphology which evolves under the influence of dynamic processes should be consistently related to quantitative resultants of the processes. Within this framework, maximum length of master watershed and the average relief of first order basins scale most nearly the same as volume yield and stormflow peaks. It is theorized, therefore, that these form elements (1) exert primary control over or are closely related to volume yield and peak flows, and (2) are better indicators of relative volume yields and peak flows than is area on the surface of the laccolith. Different morphometric characteristics, however, may be controlling elements under conditions of different parent rock and climate. Dimensionless parameters such as shape are also examined.

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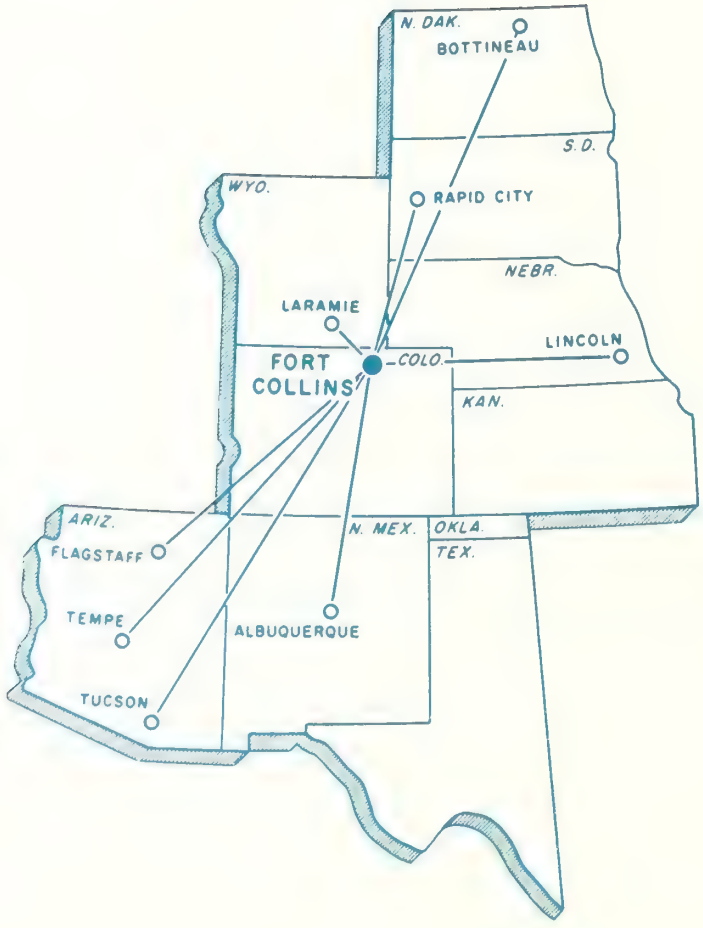
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Richard E. Francis, Richard S. Driscoll
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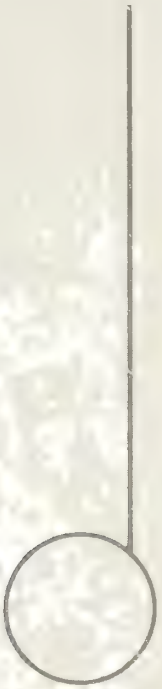

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Abstract

Frequency measured by the 3/4-inch loop technique was compared to estimates of plant basal cover, foliar cover, herbage production, and density. The relationship between loop-frequency and the other parameters were rarely significant or consistent as determined by regression and correlation. Loop-frequency unpredictably overrated foliar and basal plant cover on the basis of ratio estimates, a relative measure of bias. Therefore, frequency estimated by the 3/4-inch loop technique can be equated only to itself and not used to make inferences about other plant community parameters.

Keywords: Loop-frequency, plant basal cover, plant foliar cover, herbage production, plant density, bias (ratio estimates).

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esearch Paper RM-94

October 1972

Loop-Frequency as Related to Plant Cover, Herbage Production, and Plant Density

by

Richard E. Francis, Associate Range Scientist,
Richard S. Driscoll, Principal Plant Ecologist,
and
Jack N. Reppert, Range Scientist

Rocky Mountain Forest and Range Experiment Station[1]

[1]*Central headquarters maintained at Fort Collins, in cooperation with Colorado State University.*

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Loop-Frequency as Related to Plant Cover, Herbage Production, and Plant Density

Richard E. Francis, Richard S. Driscoll, and Jack N. Reppert

Three-quarter-inch loop-frequency is a vege-ion measurement technique which has been ed to determine change in vegetation or alyze plant communities. It is an integral t of the 3-step procedure developed by Parker 51), and was basically designed to detect nge in range condition. Loop-frequency imates presence or absence of plant species a series of small plots.

Reports have been published discussing tionships between plant frequency estimated the 3/4-inch loop and other methods for lyzing vegetation. Kinsinger et al. (1960) pared the loop method against line inter-t and variable plots to estimate shrub crown er. They reported that the loop method esti-ed cover significantly higher than "true er" or line intercept. Johnston (1957) stated t, "The loop method was the most rapid in field, detected least species, and gave the st variable data," when compared to the line rcept and vertical point quadrat methods for asuring grassland vegetation. However, loop-quency has often been interpreted as an index other community characteristics such as nt cover or density.

The objectives of this study were to deter-ne the relationships between loop-frequency a plant community measurement and (1) nt cover measured by line intercept (basal), nt quadrat (basal), and ocular estimate iar), (2) herbage production, and (3) density mbers per unit area). If loop-frequency dependably related to these other attri-es, it could be used as an index to those ributes measured and provide additional in-nation about plant community structure and nge.

Literature

Loop-frequency has been obtained by re-ding perennial plant species rooted within -inch circular plots systematically located ng 100-foot transects. When no plant base urred within the loop, plant litter, rock, e soil, or moss was recorded depending on which one of the items occupied 50 percent or more of the loop area (Parker 1951).

Tests of the loop-frequency technique have been reported by several researchers (Sharp 1954, Johnston 1957, Hutchings and Holmgren 1959, Parker and Harris 1959, Strickler 1961, Reppert and Francis[2]). The estimates of plant or soil factors within a 3/4-inch diameter loop has been referred to as a cover or density index (Parker 1951). In reality, it should be interpreted only as loop-frequency (Hutchings and Holmgren 1959) or simply frequency (Hyder et al. 1963).

Plant frequency depends on density (number per unit area) and pattern (distribution of plants) (Greig-Smith 1964). Consequently, these dependencies require consideration of various quadrat sizes to obtain satisfactory species or plant group frequency data (Hyder et al. 1965). Curtis and McIntosh (1950) and Aberdeen (1958) further emphasized that quadrat-frequency data were difficult to interpret as plant cover because of the density/dispersion dependency. In addition, Hutchings and Holmgren (1959) pointed out that loop-frequency depends upon plant shape and size, which also affects cover.

A positive bias between loop-frequency and basal or foliar cover has been reported (Parker 1950, Johnston 1957, Hutchings and Holmgren 1959, Kinsinger et al. 1960). Bias is defined as the ratio of loop-frequency to cover (Hutchings and Holmgren 1959) and approaches unity when loop-frequency and cover are nearly the same. Frequency/cover ratios were as high as 15.0 for small plants, but approached 1.0 for larger plants such as shrubs with large crowns. These results were similar to those of Parker and Harris (1959) who showed a bias of 0.97 for big and silver sagebrush[3] in California and 7.5 for grasses in Arizona.

[2] *Reppert, Jack N., and Richard E. Francis. Interpretation of trend in range condition from 3-step data. (Manuscript in preparation at Rocky Mt. Forest and Range Exp. Stn., Fort Collins, Colo.)*

[3] *Common and botanical names of plants mentioned are listed inside the back cover.*

Smith (1962) felt that changes in loop-frequency might serve as a reliable index to changes in cover provided plant sizes and bias remained fairly constant. Parker and Harris (1959) cautioned against using loop-frequency as a plant cover index when plant diameters were smaller than 1 to 2 inches, and where it cannot be assumed that the plant-size distribution remains unchanged over time.

Methods

Study Areas

Four areas were selected to represent a variety of plant communities. The Wild Bill Cattle Allotment is in the ponderosa pine-bunchgrass type on the Coconino National Forest, northwest of Flagstaff, Arizona, at 7,600 feet (Pearson and Jameson 1967). The Manitou Experimental Forest, also a pine-bunchgrass type, is located northwest of Colorado Springs, Colorado in the Pike National Forest at 7,700 feet. Manitou differed from Wild Bill in that ponderosa pine occurred in open-to-dense stands interspersed with untimbered parks (Smith 1967). The specific study site at Manitou was located in one of these parks. The Harvey Valley Allotment, northwest of Susanville, California in the Lassen National Forest, is at 5,600 feet (Ratliff et al.[4]). Three community types were selected at Harvey Valley: meadow, open grassland, and ponderosa pine-bunchgrass. The Carter Mountain-Meeteetse Creek Allotments are on the Shoshone National Forest south of Cody, Wyoming in an alpine type on an 11,000-foot volcanic plateau (Strasia et al. 1970).

Vegetation Measurements

Loop-frequency.—Loop-frequency was obtained according to standard procedures for the 3-step technique. In some cases transect length and numbers per location differed. At all locations, loop-frequency was obtained from the same transects from which other measurements were made.

Basal cover.—Plant basal cover, estimated by line intercept (Canfield 1942), was obtained at Manitou for comparison with loop-frequency. In 1967, one hundred 20-foot transects were measured. Sample size was reduced to 20 transects in 1968. These same transects were measured twice in 1969, June and August, to evaluate the relationship of the two techniques to detect plant community seasonality. The transect was the unit of comparison between the two techniques.

The vertical point quadrat method for measuring plant basal cover (Levy and Madden 1933) was used at four plot locations in each of the three vegetation types at the Harvey Valley area for comparisons with loop-frequency. Thirty transects 100 feet long were established at each location. A 3-point vertical frame, oriented perpendicular to the transect line, was systematically placed at 34 loci along each transect. The same transects were used to obtain loop-frequency data. In all cases, the transect was the sample unit.

Foliar cover.—Ocular estimates of foliar cover (Brown 1954) and loop-frequency were obtained on the Carter Mountain-Meeteetse Creek Allotments. Two 3-transect clusters, each transect 100 feet long, were randomly located within uniform sites at each of three exclosure locations, one cluster inside and one outside each exclosure. Cover was estimated by 10 percent classes on ten 4- by 8-inch plots systematically placed along each transect.

Production.—Within each of seven range units at Wild Bill, fifteen 100-foot permanent transects were established. Estimates of herbage production were obtained from three clipped plots systematically located along each transect. These plots represented one of a pair used for obtaining production-utilization by the paired-plot method (Klingman et al. 1943). The same transects were used to obtain loop-frequency data to provide comparisons between the two measurements. Four years of information, 1965-68, were obtained.

Density.—Species density (Oosting 1956) was obtained at Manitou using a 1- by 20-foot plot frame along the same transects used for basal cover and loop-frequency.

These measurement techniques, excluding loop-frequency, have been widely used and tested. They provide reliable estimates, with limited bias, of the plant community characteristics they were designed to measure (Brown 1954, NAS-NRC 1962, Hutchings and Pase 1963).

Analysis

Linear regression and correlation were used to determine the relationship between loop-

[4] *Ratliff, Raymond D., Jack N. Reppert, and R. J. McConnen. Rest-rotation grazing at Harvey Valley—range health, cattle gains, and economics. (Manuscript in preparation at Pac. Southwest Forest and Range Exp. Stn., Berkeley, Calif.)*

quency (the independent variable) and estiates of basal cover, foliar cover, production, d plant density. For each comparison, data om a transect represented an observation for gression.

Items chosen for analyses were as follows:
Loop-frequency versus percent basal cover (line intercept) for total plants and six species (Arizona fescue, blue grama, mountain muhly, trailing fleabane, pussytoes, and fringed sagebrush) by measurement date.
Loop-frequency versus percent basal cover (point quadrat) by vegetation type for total plants, three vegetation groups (grasses, forbs, and grasslikes), soil, and litter.
Loop-frequency versus percent foliar cover for total plants, two species (whiproot clover and alpine avens), and three vegetation groups (grasses, forbs, grasslikes) inside all exclosures, outside all exclosures, and all exclosure sites combined.
Loop-frequency versus production for total plants and eight species (crested wheatgrass, intermediate wheatgrass, mountain muhly, Arizona fescue, bottlebrush squirreltail, fleabane, sedge, and Fendler ceanothus) by range unit for each year and all years combined.
Loop-frequency versus density for six species (same species as 1 above) by measurement date.

Only correlation coefficients of 0.75 or eater at the 5 percent level of significance re retained. A coefficient of 0.75 accounts for about 50 percent of the variation in the dependent variable (Y). This constraint was chosen, therefore, as being statistically as well as biologically important.

Ninety-five percent confidence intervals for the true mean value of Y ($\bar{Y}$) for a given X and the slope of regression line (β) were determined when a consistently significant relationship occurred for a particular species, plant group, or soil surface characteristic. A consistently significant relationship is defined as 100 percent of the correlation coefficients for a particular test item having significant ($P = 0.05$) r values of 0.75 or greater over time.

Bias was calculated using loop-frequency data and estimates of basal and foliar cover for vegetation classes, primary plant species, and total plant species. Bias for soil and litter was calculated from data obtained by point quadrat. Bias was not calculated for either production or density because these two measurements, not being percentages, have no absolute limit as does loop-frequency or cover.

Results and Discussion

A total of 608 linear regressions were made comparing loop-frequency against four other plant community characteristics. Only 122 of the total correlation coefficients were statistically significant at $P = 0.05$ and $r \geq 0.75$ (table 1).

le 1.--Significant correlation coefficients obtained comparing 3/4-inch loop-frequency to other vegetation measurements

Vegetation type	Comparative parameters	Total tests	No. significant with $r \geq 0.75$ (P=.05)	(P=.01)
derosa pine-bunchgrass nitou)	Frequency vs. basal cover (line intercept)	252	81	44
dow rvey Valley)	Frequency vs. basal cover (pt. quadrat)	24	0	0
n-grassland rvey Valley)	Frequency vs. basal cover (pt. quadrat)	24	0	0
derosa pine-bunchgrass rvey Valley)	Frequency vs. basal cover (pt. quadrat)	22	0	0
line rter Mtn.)	Frequency vs. foliar cover	15	0	0
derosa pine-bunchgrass ld Bill)	Frequency vs. herbage production	175	15	13
derosa pine-bunchgrass nitou)	Frequency vs. density	96	26	18
TOTAL		608	122	75

1967: $Y=-0.50+.5165X$; 95% $CI(\bar{Y})= 9.0630+8.5794$; $r=.75^{**}$
1968: $Y= 0.52+.4040X$; 95% $CI(\bar{Y})= 8.9400\pm5.8769$: $r=.86^{**}$
6/1969: $Y=-3.76+.6475X$; 95% $CI(\bar{Y})=11.4700\pm6.9093$; $r=.93^{**}$
8/1969: $Y=-1.81+.5821X$; 95% $CI(\bar{Y})=10.0600\pm9.5410$; $r=.82^{**}$

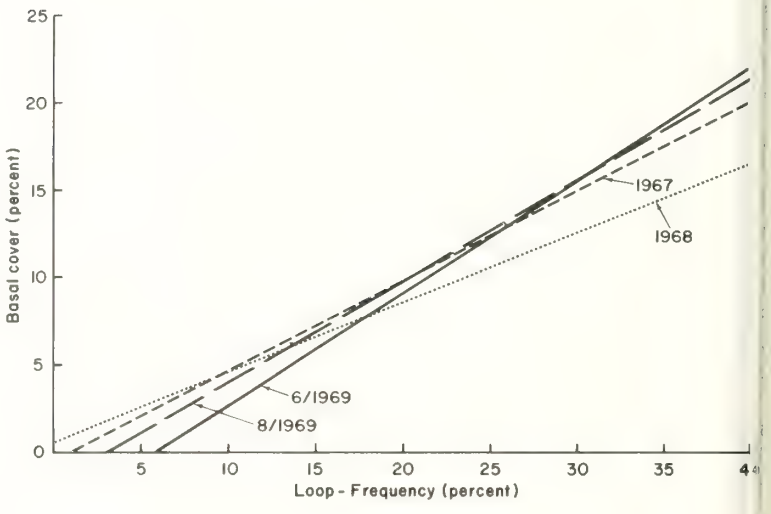

Figure 1.--Loop-frequency (X) versus basal cover (Y) measured by line intercept for blue grama; four measurement periods--Manitou. (CI for β not shown)

Basal Cover versus Loop-Frequency ... Manitou

Loop-frequency was tested against basal cover measured with line intercept by 252 linear regressions. Eighty-one significant correlation coefficients were identified (table 1). Only eight of these had a consistently significant relationship for two species over the four measurement periods; blue grama (fig. 1) and mountain muhly (fig. 2). However, the wide confidence intervals indicated doubtful reliability of the relationships. The remainder of the significant correlations were scattered among the other species and measurement periods.

Estimates of relative bias between loop-frequency and basal cover were calculated for six species and vegetation groups. The mean bias for all plants ranged from 2.3 to 2.4 for the four measurement periods (table 2). The largest range in bias was obtained for trailing fleabane (12.5 to 28.0) and the sedge species (2.4 to 20.0). The most consistent bias estimates for a vegetation group and individual species were obtained for all grasses (1.8 to 2.1) and especially for blue grama within that group.

In general, bias estimates were highly e[r]ratic except for those species previously me[n]tioned. The wide confidence bands, even wit[h] high correlation coefficients, places doubt abo[ut] an acceptable relationship between the tw[o] methods (figs. 1, 2).

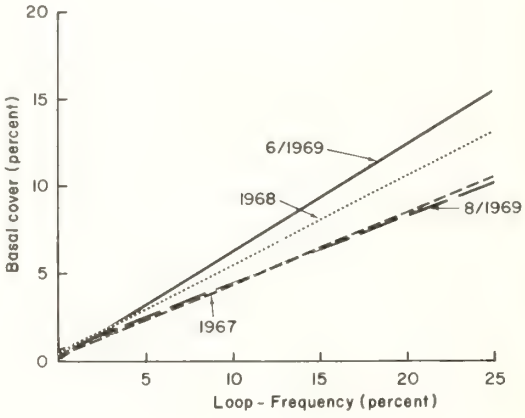

Figure 2.--Loop-frequency (X) versus basal cover (Y) measured by line intercept for mountain muhly; four measurement periods --Manitou. (CI for β not shown)

1967: $Y=.32+.4097X$; 95% $CI(\bar{Y})=2.8450+2.4601$; $r=.80$
1968: $Y=.47+.5177X$; 95% $CI(\bar{Y})=4.0600\pm3.2794$; $r=.89$
6/1969: $Y=.32+.6067X$; 95% $CI(\bar{Y})=4.7300\pm4.7982$; $r=.83$
8/1969: $Y=.67+.3811X$; 95% $CI(\bar{Y})=3.9550\pm4.3446$; $r=.76$

Basal Cover versus Loop-Frequency . . . Harvey Valley

Seventy linear regressions with related correlation coefficients were made to relate loop-frequency and basal cover measured by point quadrat in three vegetation types (table 1). None of the correlation coefficients were significant with the constraints previously defined. Thus, there was not an acceptable relationship between the two measurement techniques for the three vegetation types.

The relationships between basal cover measured by point quadrat and loop-frequency were similar to those identified comparing basal cover measured by line intercept and frequency. In all cases, loop-frequency provided a positive bias for all vegetation combinations (table 3). Generally, it was much higher with meadow-type vegetation than the other two types. Here the plants, except one of the grasses, were small in basal area, resulting in an excessively high overrating by the loop-frequency technique.

The bias relationship for the soil category in the open grassland and the litter category in the pine-bunchgrass were near unity, indicating that both methods were providing similar estimates of these items in the community (table 3). However, the extreme variation in bias ratios among species and vegetation classes between the point quadrat and loop-frequency sampling techniques within and among the three vegetation types indicates that the relationship between the two techniques is of limited value.

Foliar Cover versus Loop-Frequency . . . Carter Mountain

To test the relationship between loop-frequency and foliar cover, 15 linear regressions with related correlation coefficients were made for combinations of exclosure sites and species. None of the correlation coefficients were significant with the constraints previously defined. Thus, there is no apparent acceptable relationship between the two measurement techniques in alpine vegetation.

The bias between loop-frequency and foliar cover ranged from 0.5 for alpine avens to 6.0 for Junegrass (table 4). For individual plant classes, the bias ratio was 2.9, 3.0, and 1.6 for grasses, grasslikes, and forbs, respectively. Due to the wide range in bias within the same group of species, loop-frequency could not be converted to foliar cover by a mean bias estimate.

Loop-frequency can be expected to be only haphazardly related to foliar cover. The loop is measuring presence or absence of vegetation at the ground surface without regard to aboveground configuration. Theoretically there should be no change in loop-frequency provided seasonality does not alter plant community structure or composition (Greig-Smith 1964).

Foliar cover is an estimate of aboveground leafage and will vary with seasons from year to year, depending on growing conditions and animal grazing. If the area were sampled when the vegetation had attained its maximum

Table 2.--Magnitude and variability of mean frequency, cover, and bias between 3/4-inch loop-frequency and basal cover by line intercept in a ponderosa pine-bunchgrass type--Manitou

Species	June 1967			August 1968			June 1969			August 1969		
	Freq.	Cover	Bias	Freq.	Cover	Bias	Freq.	Cover	Bias	Freq.	Cover	Bias
	Percent			Percent			Percent			Percent		
All grasses:	26.3	12.5	2.1	29.5	14.8	1.9	32.6	17.2	1.8	31.4	15.1	2.1
Blue grama	18.5	9.1	2.0	20.8	9.5	2.2	23.5	11.4	2.0	20.4	10.0	2.0
Arizona fescue	0.3	0.1	3.0	1.0	0.6	1.6	1.1	0.5	2.2	0.8	0.5	1.6
Mountain muhly	6.1	2.8	2.2	6.9	4.0	1.7	7.2	4.9	1.4	8.6	3.9	2.2
Grasslikes (sedge):	0.4	0.1	4.0	1.2	0.5	2.4	2.0	0.1	20.0	1.8	0.3	6.0
All forbs:	20.2	6.4	3.2	14.9	3.6	4.1	16.7	4.4	3.8	14.0	4.8	2.9
Pussytoes	10.5	4.9	2.1	5.0	2.4	2.0	8.1	3.4	2.4	8.4	4.2	2.0
Trailing fleabane	4.2	0.3	14.0	5.4	0.4	13.5	2.5	0.2	12.5	2.8	0.1	28.0
Fringed sagebrush	2.3	0.4	5.8	2.1	0.4	5.2	1.9	0.6	3.2	1.6	0.4	4.0
All plants:	46.9	19.0	2.4	45.6	18.9	2.4	51.3	21.7	2.4	47.2	20.2	2.3

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Frequency measured by the 3/4-inch loop technique was compared to estimates of plant basal cover, foliar cover, herbage production, and density. The relationship between loop-frequency and the other parameters were rarely significant or consistent as determined by regression and correlation. Loop-frequency unpredictably overrated foliar and basal plant cover on the basis of ratio estimates, a relative measure of bias. Therefore, frequency estimated by the 3/4-inch loop technique can be equated only to itself and not used to make inferences about other plant community parameters.

Keywords: Loop-frequency, plant basal cover, plant foliar cover, herbage production, plant density, bias (ratio estimates).

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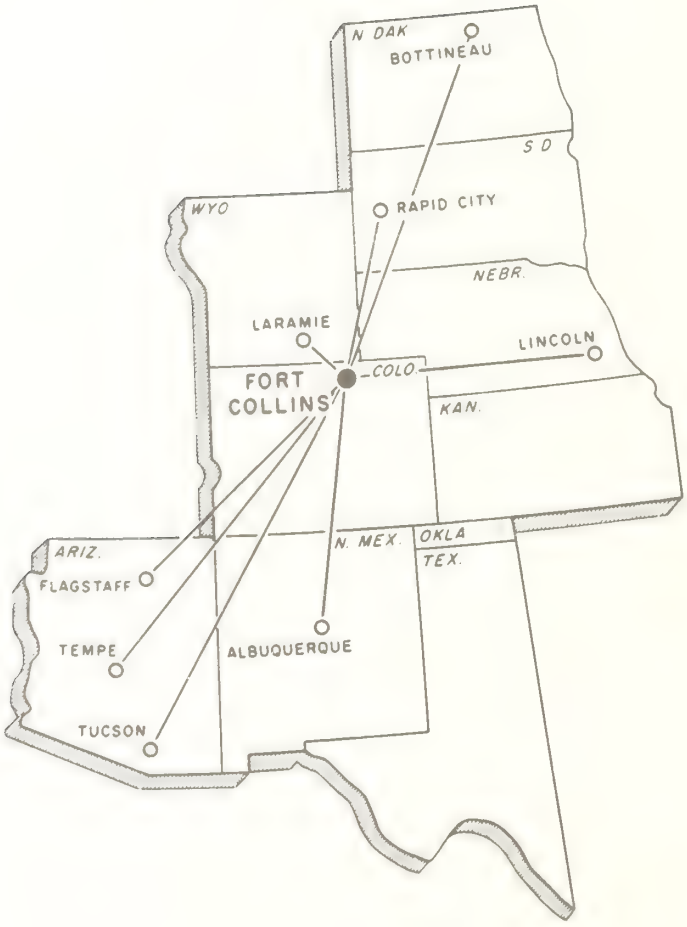
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USDA Forest Service Research Paper RM-95 October 1972

Volume Tables and Point-Sampling Factors For Engelmann Spruce in Colorado and Wyoming

By
Clifford A. Myers and Carleton B. Edminster

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FEB 1

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FOREST SERVICE U. S. DEPARTMENT OF AGRICULTURE

ABSTRACT

Volumes are in total cubic feet and cubic feet to a 4.0-inch top, board feet Scribner Rule to 6-inch and 8-inch tops, and board feet International ¼-inch Rule to 6-inch and 8-inch tops. Tree heights are in feet and numbers of logs. Volume equations are of the form $V = a + bD^2H$.

Keywords: Tree volume tables, tree volume estimates, stand volume estimates, *Picea engelmannii.*

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esearch Paper RM-95

October 1972

Volume Tables and Point-Sampling Factors for Engelmann Spruce in Colorado and Wyoming

by

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Volume Tables and Point-Sampling Factors for Engelmann Spruce in Colorado and Wyoming

Clifford A. Myers and Carleton B. Edminster

Nineteen tables presented here give values eded to determine the volumes of Engelmann ruce (Picea engelmannii Parry) trees in olorado and southern Wyoming. They provide e following:

Gross volumes in total and merchantable cubic feet.
Gross volumes in board feet, Scribner and International ¼-inch log rules.
Point-sampling factors for merchantable cubic feet and board feet.

Volume on an area may be determined om: (1) measurements of tree diameters and ights, (2) measurements of diameters and sufficient heights to convert the appropriate lume tables to local volume tables (Chapman d Meyer 1949), or (3) tree counts obtained point-sampling.

Sample trees were measured by personnel the Colorado State Forest Service and of the SDA Forest Service on the following eight tional Forests: Arapaho, Grand Mesa-Uncompahgre, Gunnison, Medicine Bow, Rio ande, Routt, San Juan, and White River.

Definitions and Standards

Variables used in the tables, and standards llowed in field measurement and computaons, are as follows:

Diameter breast high (d.b.h.). — Measured 0.1 inch outside bark 4.5 feet above ground vel at the uphill side of the tree. Full-inch ameter classes, with class midpoints at the lf-inch marks, were used in the tables (12.5, 5, and so forth).

Scaling diameter of logs. — Average diameter inside bark to 0.1 inch, measured at the upper (small) end of logs or half-logs. Saw-log diameter classes followed conventional scaling practice, with class midpoints at whole inches (12.0, 13.0, and so forth).

Minimum top diameters for board-foot volumes. — Two minimum top diameters inside bark, 6 and 8 inches. Actual utilization practices indicate that both limits are used for Engelmann spruce, and that the limit does not vary with tree diameter. Logs with a scaling diameter less than 5.6 inches for the 6-inch top and 7.6 inches for the 8-inch top usually were not included in saw-log volume. A few logs with smaller scaling diameters were included to satisfy requirements of the 4-foot rule, described below. This also conforms to local practice.

Total height. — Measured to the nearest foot from ground level at the tree base upward to the tip. Forked, stag-topped, or other deformed trees were not included in the sample. Midpoints of the total height classes used in the tables were multiples of 10.0 feet.

Height in logs. — Measured from the top of a stump 1.0 foot high upward to the limit of saw-log utilization. Each tree was divided into as many 16.5-foot-long logs as possible. An additional half-log, if present, was taken from the uppermost part of the merchantable length. Portions of the bole above the height of minimum top saw-log diameter were included in the uppermost saw-log if the standard length of the log or half-log ended within 4.0 feet above this height. This "4-foot rule" was used to avoid biased negative error in volume (Chapman and Meyer 1949).

Explanation of Tables

General definitions and standards given above apply to all tables. Explanation of each type of table and suggestions for use are presented here.

Volume Tables

Headings and footnotes with each volume table (table 1 and even-numbered tables) give the volume unit, type of height measurement, utilization standards, and volume equations used in its compilation. Ten-foot or half-log height classes and full-inch diameter classes were used in all tables.

The volume tables were derived from linear regressions in V and D^2H, of the form:

$$V = a + b\,D^2H$$

where:

V = gross volume in the appropriate unit,
D = diameter breast high outside bark,
H = total height in feet or in standard logs and half-logs, and
a, b = regression constants.

Two equations were used to derive each table except for table 8. Usually, the relationship between V and D^2H could not be expressed by a single linear regression over the full range of the basic data.

The number of logs in a tree shown in the tables is not necessarily the number that will actually be cut from it. Instead, it is the number of logs between the 1.0-foot stump and the height where minimum top diameter is reached. Volume of nonmerchantable logs below the height of minimum top diameter should be deducted from tree volume by: (1) estimation of scaling diameters and deduction of appropriate log volumes, (2) use of taper tables to determine scaling diameters and deduction of log volumes, or (3) reduction of total volume by the percentage of volume contained in the nonmerchantable log. Volume must not be reduced by tallying fewer logs in the tree.

Point-Sampling Factors

Tables of point-sampling factors (odd-numbered tables from 3 to 19, inclusive) give the factors for each of numerous combinations of tree diameter and height. Tabulated volumes per square foot of basal area were obtained from the equations in the table footnotes. These equations resulted from the division of each term of the corresponding tree volume equation by $0.005454D^2$, a formula for basal area (B).

Point-sample cruising for volume can b done in several ways: (1) measure the diamete and height of each tree counted through th prism or relascope, (2) measure the height c each counted tree and estimate its diamete or (3) measure the heights of the counted tree and make no record of the diameters. The pr cedure selected will depend on the accurac desired (relative accuracy usually in the orde listed above) and the time and personnel avai able for the job.

If the diameter and height of each counte tree are measured, a volume conversion facto is selected for each combination of diamete and height. Factors are read from the appropr ate factor table (odd-numbered tables from to 19, inclusive) or computed from equation in the table footnotes. Volume per acre is com puted as follows:

1. Multiply the number of counted trees in eac diameter-height class by the point-samplin factor for the class.
2. Total the products of step one.
3. Multiply this total by the basal area facto of the prism or other angle gage used.
4. Divide the product of step three by the num ber of points sampled on the tract.

Time can often be saved if the heights o the counted trees are measured, while diameter are estimated and tallied by broad diamete classes. Inspection of the factor tables show that volumes per square foot of basal are often do not differ greatly among trees of single height class. For example, the merchant able cubic volumes of trees 70 feet tall var from 26.2 to 29.4 cubic feet per square foot a diameter increases from 5 to 23 inches (tabl 3). Board feet per square foot of basal are changes little with diameter when tree height are measured in logs (tables 7, 11, 15, 19) Therefore, the increased time spent measurin diameters may not increase accuracy materially

It is recommended that diameters not b recorded at all when the distribution of diam eters and heights on the area inventoried in dicates there is little change in volume pe square foot within a height class. Point-sampl ing factors based on height only can be com puted from the factor tables given here.

The factor for each height class can be computed using almost the same procedure used to derive a local volume table from a standard table (Chapman and Meyer 1949). Diameters are plotted over heights, since height will be retained as the measured variable.

The techniques of point sampling have been adequately described in numerous publications (Bonnett 1959, Grosenbaugh 1952, 1955, 1958).

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Cubic feet inside bark

Entire stem including stump and top — Total height above ground

Diameter breast height outside bark (Inches)	Total height in feet: 10	20	30	40	50	60	70	80	90	100	110	120	130	Basis: Trees
	Volume in cubic feet													
1	0.12	0.17												21
2	0.21	0.36	0.51	0.66										25
3	0.36	0.65	0.94	1.24	1.53									25
4	0.55	1.03	1.52	2.00	2.48									20
5		1.51	2.23	2.96	3.68	4.40								26
6		2.08	3.09	4.10	5.11	6.12	7.13							24
7			4.10	5.44	6.79	8.13	9.48	10.8						19
8			5.24	6.97	8.70	10.4	12.2	13.9						28
9			6.54	8.69	10.8	13.0	15.2	17.3						22
10			7.97	10.6	13.2	15.9	18.5	21.1	23.8					21
11				12.7	15.9	19.0	22.2	25.4	28.5	31.7				40
12					18.7	22.5	26.2	29.9	33.7	37.4				42
13					21.8	26.2	30.6	34.9	39.3	43.6				11
14						30.2	35.2	40.3	45.3	50.3	55.1			19
15						34.5	40.3	46.0	51.7	56.8	61.4			21
16						39.1	45.6	52.1	57.7	63.0	68.2			17
17						44.0	51.3	57.7	63.6	69.5	75.4	81.3		11
18							56.7	63.3	69.9	76.5	83.1	89.7		13
19							61.8	69.1	76.5	83.8	91.1	98.5		11
20							67.2	75.3	83.4	91.5	99.6	108	116	13
21							72.9	81.8	90.7	99.6	109	117	126	10
22							78.8	88.6	98.4	108	118	128	137	5
23							85.0	95.7	106	117	128	138	149	7
24								103	115	126	138	149	161	9
25								111	123	136	148	161	174	6
26								119	132	146	160	173	187	4
27								127	142	156	171	186	200	7
28									152	167	183	199	214	4
29									162	178	195	212	229	4
30									172	190	208	226	244	3
31									183	202	221	240	259	1
32										214	235	255	275	2
33											249	270	292	0
34												286	309	1
35												302	327	0
36												319	345	1
Basis: No. trees	35	36	28	40	40	57	69	64	46	46	25	4	3	493

Block indicates extent of basic data.

Derived from: $V = 0.00239\ D^2H + 0.06439$, for D^2H to 22,500

$V = 0.00193\ D^2H + 10.41663$, for D^2H larger than 22,500

Standard errors of estimate: ± 13.24 percent; ± 9.29 percent

Diameter classes full-inch: e.g. 20-inch class includes 20.0 to 20.9

Table 6.--Gross volumes in board feet Scribner Rule, Engelmann spruce in Colorado and Wyoming

Board feet inside bark
Merchantable stem excluding stump and top

Top diameter 6 inches inside bark
Stump height 1.0 foot

Diameter breast height outside bark (Inches)	Number of 16-foot logs to 6-inch top													Basis: Trees
	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0	6.5	7.0	
	Volume in board feet													
7	19	25	32											19
8	22	31	39	48										28
9	27	37	48	58	69									22
10	31	44	57	70	83	96								22
11	36	52	68	83	99	114	130							40
12		61	79	97	116	134	152	171						42
13			91	113	134	155	177	198						11
14				129	154	178	203	228	253					19
15				147	175	203	231	260	288					21
16				165	197	230	262	294	326	358				17
17				185	221	258	294	330	366	402				11
18					247	287	327	368	408	448	488			13
19					274	318	363	408	453	497	542			11
20					302	351	401	450	500	549	598	647		13
21						386	440	495	549	603	657	710		10
22						422	482	541	601	659	718	776		5
23						460	525	590	654	718	781	845		7
24						500	570	640	709	779	848	917		9
25						541	617	692	767	842	917	992		6
26						584	665	746	827	908	989	1070		4
27						627	715	802	889	977	1064	1151		7
28							767	860	954	1048	1142	1236		4
29								921	1021	1122	1222	1323		4
30								983	1090	1198	1305	1413	1520	3
31								1047	1162	1277	1391	1506	1620	1
32									1236	1358	1480	1602	1724	2
33										1442	1571	1701	1831	0
34											1666	1803	1941	1
35											1763	1908	2054	0
36											1862	2016	2170	1
Basis: No. trees	31	34	29	42	39	50	37	35	28	21	4	2	1	353

Block indicates extent of basic data.
Derived from: $V = 0.23522\ D^2L + 5.37508$, for D^2L to 2530
$V = 0.23097\ D^2L + 16.11994$, for D^2L larger than 2530
Standard errors of estimate: ± 15.05 percent; ± 11.92 percent
Diameter classes full-inch; e.g. 20-inch class includes 20.0 to 20.9

Table 7.--Gross volumes in board feet Scribner Rule per square foot of basal area, Engelmann spruce in Colorado and Wyoming

Board feet inside bark
Merchantable stem excluding stump and top

Top diameter 6 inches inside bark
Stump height 1.0 foot

Diameter breast height outside bark (Inches)	Number of 16-foot logs to 6-inch top												
	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0	6.5	7.0
	Board feet												
7	61	82	104										
8	57	78	100	121									
9	54	76	97	119	140								
10	52	74	95	117	138	160							
11	51	72	94	115	137	158	180						
12		71	93	114	136	157	179	200					
13			92	113	135	156	178	199					
14				113	134	156	177	199	220				
15				112	133	155	177	198	220				
16				111	133	155	176	198	219	241			
17				111	133	154	176	197	219	240			
18					132	154	175	197	219	240	262		
19					132	154	175	197	218	240	261		
20					132	153	175	196	218	240	261	282	
21						153	175	196	218	239	260	282	
22						153	174	196	218	239	260	281	
23						153	174	196	217	238	259	281	
24						153	174	195	217	238	259	280	
25						152	174	195	216	237	259	280	
26						152	174	195	216	237	258	279	
27						152	173	194	216	237	258	279	
28							173	194	215	237	258	279	
29								194	215	236	257	279	
30								194	215	236	257	278	300
31								194	215	236	257	278	299
32									215	236	257	278	299
33										236	257	278	299
34											257	278	299
35											256	278	299
36											256	277	299

Derived from: $V/B = 43.1280\ L + 985.5299/D^2$, above dotted line.
$V/B = 42.3487\ L + 2955.6179/D^2$, below dotted line.

Diameter classes full-inch; e.g. 20-inch class includes 20.0 to 20.9

Table 8.--Gross volumes in board feet Scribner Rule, Engelmann spruce in Colorado and Wyoming

Board feet inside bark — Top diameter 8 inches inside bark
Merchantable stem excluding stump and top — Stump height 1.0 foot

Diameter breast height outside bark (inches)	Total height in feet										Basis: Trees
	40	50	60	70	80	90	100	110	120	130	
	Volume in board feet										
10	15	28	41	55	68	82					23
11	25	41	57	74	90	106	122				41
12		56	75	94	113	132	151				42
13		72	94	116	138	160	182				12
14		89	114	140	165	191	216	242			24
15			136	165	195	224	253	282			24
16			160	193	226	259	292	325			22
17			184	221	259	296	333	370	408		15
18				252	294	335	377	418	460		16
19				284	331	377	423	469	515		12
20				318	370	421	472	523	574	625	13
21				354	410	467	523	579	635	691	12
22				392	453	515	576	638	699	761	6
23				431	498	565	632	699	766	833	7
24					544	617	690	763	836	909	9
25					593	672	751	830	909	988	6
26					644	729	814	900	985	1070	5
27					696	788	880	972	1064	1156	7
28						849	948	1047	1145	1244	4
29						913	1018	1124	1230	1336	4
30						978	1091	1204	1317	1430	3
31						1046	1167	1287	1408	1528	1
32							1244	1373	1501	1629	2
33								1461	1597	1734	0
34									1696	1841	1
35									1798	1952	0
36									1903	2065	1
Basis: No. trees	1	7	31	68	72	53	48	25	4	3	312

Block indicates extent of basic data

Derived from: $V = 0.01215\ D^2H - 38.96822$

Standard error of estimate: $\pm$ 16.40 percent

Diameter classes full-inch; e.g. 20-inch class includes 20.0 to 20.9

Table 9.--Gross volumes in board feet Scribner Rule per square foot of basal area, Engelmann spruce in Colorado and Wyoming

Board feet inside bark
Merchantable stem excluding stump and top

Top diameter 8 inches inside bark
Stump height 1.0 foot

Diameter breast height outside bark (Inches)	Total height in feet									
	40	50	60	70	80	90	100	110	120	130
	Board feet									
10	24	47	69	91	113	136				
11	35	57	80	102	124	146	169			
12		66	88	110	132	155	177			
13		72	94	117	139	161	184			
14		77	100	122	144	167	189	211		
15			104	126	148	171	193	215		
16			107	130	152	174	197	219		
17			110	133	155	177	199	222	244	
18				135	157	180	202	224	246	
19				137	159	182	204	226	249	
20				139	161	183	206	228	250	273
21				140	163	185	207	230	252	274
22				142	164	186	209	231	253	275
23				143	165	188	210	232	254	277
24					166	189	211	233	255	278
25					167	190	212	234	256	279
26					168	190	213	235	257	279
27					169	191	213	236	258	280
28						192	214	236	259	281
29						192	215	237	259	281
30						193	215	237	260	282
31						193	216	238	260	282
32							216	238	261	283
33								239	261	283
34									261	284
35									262	284
36									262	284

Derived from: $V/B = 2.2277\ H - 7144.8882/D^2$

Diameter classes full-inch; e.g. 20-inch class includes 20.0 to 20.9

Table 10.--Gross volumes in board feet Scribner Rule, Engelmann spruce in Colorado and Wyoming

Board feet inside bark
Merchantable stem excluding stump and top

Top diameter 8 inches inside bark
Stump height 1.0 foot

Diameter breast height outside bark (Inches)	Number of 16-foot logs to 8-inch top													Basis: Trees
	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0	6.5	7.0	
	Volume in board feet													
10	37	51	65	79										23
11	42	59	76	93	110									41
12	48	68	89	109	129	149								42
13		79	102	125	149	172	196							12
14		89	116	143	170	198	225	252						24
15			132	163	194	225	255	286						24
16			148	183	218	253	288	322	355					22
17			166	205	245	284	322	359	396					15
18				228	272	316	357	398	439	480				16
19				253	302	348	393	439	484	530				12
20					331	381	432	482	532	583	633			13
21					361	416	472	527	583	638	694			12
22					393	453	514	575	636	696	757			6
23					426	492	558	625	691	757	823			7
24						532	604	676	748	820	892			9
25						574	652	730	808	886	964			6
26						618	702	786	871	955	1039			5
27						663	754	845	935	1026	1117			7
28							808	905	1003	1100	1197			4
29							863	968	1072	1177	1281	1385	1490	4
30							921	1033	1144	1256	1367	1479	1590	3
31								1099	1218	1337	1456	1575	1694	1
32								1169	1295	1422	1549	1675	1802	2
33									1374	1509	1644	1778	1913	0
34											1741	1884	2027	1
35											1842	1993	2144	0
36											1946	2106	2265	1
Basis: No. Trees	15	27	41	42	45	43	33	29	23	8	4	2	0	312

Block indicates extent of basic data.
Derived from: $V = 0.25726\ D^2L + 8.19211$, for D^2L to 1160
$V = 0.23987\ D^2L + 28.40381$, for D^2L larger than 1160
Standard errors of estimate: ± 12.43 percent; ± 10.79 percent
Diameter classes full-inch; e.g. 20-inch class includes 20.0 to 20.9

Table 11.--Gross volumes in board feet Scribner Rule per square foot of basal area, Engelmann spruce in Colorado and Wyoming

Board feet inside bark
Merchantable stem excluding stump and top

Top diameter 8 inches inside bark
Stump height 1.0 foot

Diameter breast height outside bark (Inches)	Number of 16-foot logs to 8-inch top												
	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0	6.5	7.0
	Board feet												
10	61	84	108	132									
11	59	82	106	129	153								
12	57	80	104	128	151	175							
13		79	103	126	150	173	197						
14		78	101	125	149	172	196	219					
15			101	124	148	171	195	219					
16			100	123	147	171	194	217	239				
17			99	123	146	170	193	215	237				
18				122	146	169	191	213	235	257			
19				122	145	168	190	212	234	256			
20					144	166	188	210	232	254	276		
21					143	165	187	209	231	253	275		
22					142	164	186	208	230	252	274		
23					141	163	185	207	229	251	273		
24						163	185	207	229	251	273		
25						162	184	206	228	250	272		
26						161	183	205	227	249	271		
27						161	183	205	227	249	271		
28							182	204	226	248	270		
29							182	204	226	248	270	292	314
30							182	204	226	247	269	291	313
31								203	225	247	269	291	313
32								203	225	247	269	291	313
33									225	247	269	291	313
34											268	290	312
35											268	290	312
36											268	290	312

Derived from: $V/B = 47.1691\ L + 1502.0370/D^2$, above dotted line
$V/B = 43.9806\ L + 5207.8860/D^2$, below dotted line

Diameter classes full-inch; e.g. 20-inch class includes 20.0 to 20.9

Table 12.--Gross volumes in board feet International 1/4-inch Rule, Engelmann spruce in Colorado and Wyoming

Board feet inside bark
Merchantable stem excluding stump and top

Top diameter 6 inches inside bark
Stump height 1.0 foot

Diameter breast height outside bark (Inches)	Total height in feet										Basis: Trees
	40	50	60	70	80	90	100	110	120	130	
	Volume in board feet										
7	6	14	21	29	37						19
8	15	25	35	45	55						28
9	25	37	50	62	75						22
10	36	51	66	82	97	112					22
11	48	66	85	103	122	140	158				40
12		83	105	127	148	170	192				42
13		101	126	152	177	203	228				11
14		121	150	179	208	238	267	296			19
15			175	208	242	275	309	342			21
16			202	239	277	315	353	387			17
17			230	273	315	357	395	433	471		11
18				308	355	397	440	482	524		13
19				345	393	440	487	534	581		11
20				380	432	484	536	588	640	692	13
21				417	474	531	588	645	702	759	10
22				455	517	580	642	705	767	830	5
23				494	563	631	699	767	835	904	7
24					610	684	758	832	907	981	9
25					659	740	820	900	981	1061	6
26					711	798	884	971	1058	1144	4
27					764	858	951	1044	1138	1231	7
28						920	1020	1120	1221	1321	4
29						984	1092	1199	1307	1414	4
30						1051	1166	1281	1396	1511	3
31						1120	1242	1365	1488	1610	1
32							1321	1452	1582	1713	2
33								1542	1680	1819	0
34									1781	1928	1
35									1885	2040	0
36									1991	2156	1
Basis: No. Trees	13	26	54	69	63	48	48	25	4	3	353

Block indicates extent of basic data.

Derived from: $V = 0.01391\ D^2H - 25.61022$, for D^2H to 27,300

$V = 0.01235\ D^2H + 17.02079$, for D^2H larger than 27,300

Standard errors of estimate: $\pm$ 18.12 percent; $\pm$ 11.98 percent

Diameter classes full-inch; e.g. 20-inch class includes 20.0 to 20.9

Table 13.--Gross volumes in board feet International 1/4-inch Rule per square foot of basal area, Engelmann spruce in Colorado and Wyoming

Board feet inside bark
Merchantable stem excluding stump and top

Top diameter 6 inches inside bark
Stump height 1.0 foot

Diameter breast height outside bark (Inches)	Total height in feet									
	40	50	60	70	80	90	100	110	120	130
	Board feet									
7	19	44	70	95	121					
8	37	63	88	114	139					
9	50	75	101	126	152					
10	59	85	110	136	161	187				
11	67	92	118	143	169	194	220			
12		97	123	148	174	199	225			
13		102	127	153	178	204	229			
14		105	131	156	182	207	233	258		
15			133	159	184	210	235	261		
16			136	161	187	212	238	261		
17			138	163	189	214	237	259	282	
18				165	190	213	236	258	281	
19				166	189	212	235	257	280	
20				166	189	211	234	257	279	302
21				165	188	211	233	256	278	301
22				165	187	210	233	255	278	301
23				164	187	209	232	255	277	300
24					186	209	232	254	277	300
25					186	209	231	254	277	299
26					186	208	231	254	276	299
27					185	208	231	253	276	298
28						208	230	253	276	298
29						207	230	253	275	298
30						207	230	252	275	298
31						207	230	252	275	298
32							229	252	275	297
33								252	275	297
34									274	297
35									274	297
36									274	297

Derived from: $V/B = 2.5504\ H - 4695.6766/D^2$, above dotted line
$V/B = 2.2644\ H + 3120.7902/D^2$, below dotted line

Diameter classes full-inch; e.g. 20-inch class includes 20.0 to 20.9

Table 14.--Gross volumes in board feet International 1/4-inch Rule, Engelmann spruce in Colorado and Wyoming

Board feet inside bark
Merchantable stem excluding stump and top

Top diameter 6 inches inside bark
Stump height 1.0 foot

Diameter breast height outside bark (Inches)	Number of 16-foot logs to 6-inch top													Basis: Trees
	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0	6.5	7.0	
	Volume in board feet													
7	20	28	36											19
8	24	34	45	55										28
9	29	42	55	68	80									22
10	35	51	66	82	97	113								22
11	41	60	79	97	116	135	153							40
12		70	92	114	136	158	180	203						42
13			107	133	158	184	210	236						11
14				152	182	212	242	271	301					19
15				174	208	242	275	309	343					21
16				196	235	273	312	350	388	420				17
17				220	264	307	350	392	428	464				11
18					294	342	390	430	471	511	551			13
19					326	380	426	471	515	560	605			11
20					360	414	463	513	563	612	662	712		13
21						449	503	558	612	667	721	776		10
22						485	545	604	664	724	784	844		5
23						523	588	653	719	784	849	914		7
24						563	633	704	775	846	917	988		9
25						604	681	757	834	911	988	1065		6
26						647	730	813	896	979	1062	1144		4
27						692	781	870	959	1049	1138	1227		7
28							834	930	1026	1121	1217	1313		4
29								991	1094	1197	1300	1402		4
30								1055	1165	1275	1385	1494	1604	3
31								1121	1238	1355	1472	1590	1707	1
32									1314	1438	1563	1688	1813	2
33										1524	1657	1789	1922	0
34											1753	1894	2034	1
35											1852	2001	2150	0
36											1954	2112	2269	1
Basis: No. Trees	31	34	29	42	39	50	37	35	28	21	4	2	1	353

Block indicates extent of basic data.

Derived from: $V = 0.28272\ D^2L + 3.79359$, for D^2L to 1350

$V = 0.23616\ D^2L + 66.44465$, for D^2L larger than 1350

Standard errors of estimate: $\pm$ 15.12 percent; $\pm$ 11.35 percent

Diameter classes full-inch; e.g. 20-inch class includes 20.0 to 20.9

Table 15.--Gross volumes in board feet International 1/4-inch Rule per square foot of basal area, Engelmann spruce in Colorado and Wyoming

Board feet inside bark
Merchantable stem excluding stump and top

Top diameter 6 inches inside bark
Stump height 1.0 foot

Diameter breast height outside bark (Inches)	Number of 16-foot logs to 6-inch top												
	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0	6.5	7.0
	Board feet												
7	64	90	116										
8	61	87	113	139									
9	60	85	111	137	163								
10	58	84	110	136	162	188							
11	57	83	109	135	161	187	213						
12		82	108	134	160	186	212	238					
13			107	133	159	185	211	237					
14				133	159	185	211	237	262				
15				132	158	184	210	236	262				
16				132	158	184	210	236	261	283			
17				132	158	184	210	235	256	278			
18					158	183	209	230	252	274	295		
19					157	183	205	227	249	270	292		
20					157	181	202	224	245	267	289	310	
21						178	200	221	243	265	286	308	
22						176	197	219	241	262	284	306	
23						174	195	217	239	260	282	304	
24						172	193	215	237	258	280	302	
25						170	192	214	235	257	279	300	
26						169	191	212	234	255	277	299	
27						168	189	211	233	254	276	298	
28							188	210	232	253	275	296	
29								209	231	252	274	295	
30								208	230	251	273	295	316
31								207	229	250	272	294	315
32									228	250	271	293	315
33										249	271	292	314
34											270	292	313
35											269	291	313
36											269	291	312

Derived from: $V/B = 51.8372\ L + 695.5611/D^2$, above dotted line

$V/B = 43.3003\ L + 12182.7374/D^2$, below dotted line

Diameter classes full-inch; e.g. 20-inch class includes 20.0 to 20.9

Table 16.--Gross volumes in board feet International 1/4-inch Rule, Engelmann spruce in Colorado and Wyoming

Board feet inside bark
Merchantable stem excluding stump and top

Top diameter 8 inches inside bark
Stump height 1.0 foot

Diameter breast height outside bark (Inches)	Total height in feet										Basis: Trees
	40	50	60	70	80	90	100	110	120	130	
	Volume in board feet										
10	18	33	49	65	80	96					23
11	30	49	68	86	105	123	142				41
12		66	88	110	132	154	176				42
13		84	110	135	161	187	212				12
14		104	133	163	193	222	249	276			24
15			159	193	226	257	288	319			24
16			186	224	259	294	329	364			22
17			214	254	294	333	373	412	452		15
18				287	331	375	419	463	507		16
19				321	370	419	468	517	566		12
20				357	411	465	519	574	628	682	13
21				395	455	514	573	633	692	752	12
22				435	500	565	630	695	760	826	6
23				476	547	618	689	760	831	903	7
24					597	674	751	828	906	983	9
25					648	732	815	899	983	1067	6
26					702	792	882	973	1063	1154	5
27					757	855	952	1049	1147	1244	7
28						919	1024	1128	1233	1338	4
29						987	1099	1211	1323	1435	4
30						1056	1176	1296	1415	1535	3
31						1128	1256	1383	1511	1639	1
32							1338	1474	1610	1746	2
33								1567	1712	1856	0
34									1817	1970	1
35									1925	2087	0
36									2036	2208	1
Basis: No. Trees	1	7	31	68	72	53	48	25	4	3	312

Block indicates extent of basic data.

Derived from: $V = 0.01407\ D^2H - 44.08214$, for D^2H to 18,900

$V = 0.01287\ D^2H - 21.43152$, for D^2H larger than 18,900

Standard errors of estimate: $\pm$ 17.12 percent; $\pm$ 15.95 percent

Diameter classes full-inch; e.g. 20-inch class includes 20.0 to 20.9

Table 17.--Gross volumes in board feet International 1/4-inch Rule per square foot of basal area, Engelmann spruce in Colorado and Wyoming

Board feet inside bark
Merchantable stem excluding stump and top

Top diameter 8 inches inside bark
Stump height 1.0 foot

Diameter breast height outside bark (Inches)	Total height in feet									
	40	50	60	70	80	90	100	110	120	130
	Board feet									
10	30	56	81	107	133	159				
11	42	68	94	119	145	171	197			
12		77	103	129	155	180	206			
13		85	110	136	162	188	214			
14		91	116	142	168	194	217	241		
15			121	147	172	196	220	243		
16			125	151	174	198	222	245		
17			128	152	176	200	223	247	270	
18				154	177	201	224	248	272	
19				155	178	202	226	249	273	
20				156	179	203	227	250	274	297
21				157	180	204	227	251	275	298
22				157	181	205	228	252	275	299
23				158	182	205	229	252	276	300
24					182	206	229	253	277	300
25					183	206	230	254	277	301
26					183	207	230	254	278	301
27					184	207	231	254	278	302
28						208	231	255	278	302
29						208	231	255	279	302
30						208	232	255	279	303
31						208	232	256	279	303
32							232	256	279	303
33								256	280	303
34									280	303
35									280	304
36									280	304

Derived from: $V/B = 2.5798\ H - 8082.5339/D^2$, above dotted line
$V/B = 2.3597\ H - 3929.5049/D^2$, below dotted line

Diameter classes full-inch; e.g. 20-inch class includes 20.0 to 20.9

Table 18.--Gross volumes in board feet International 1/4-inch Rule, Engelmann spruce in Colorado and Wyoming

Board feet inside bark
Merchantable stem excluding stump and top

Top diameter 8 inches inside bark
Stump height 1.0 foot

Diameter breast height outside bark (Inches)	Number of 16-foot logs to 8-inch top													Basis: Trees
	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0	6.5	7.0	
	Volume in board feet													
10	42	59	76	93										23
11	49	69	90	110	131									41
12	56	80	105	129	153	177								42
13		92	121	149	177	205	233							12
14		105	138	170	203	235	268	300						24
15			156	193	231	268	305	340						24
16			176	218	260	302	342	376	409					22
17			197	244	292	338	376	414	451					15
18				272	325	369	411	454	496	538				16
19				301	355	402	449	496	543	589				12
20				332	385	436	488	540	592	644	695			13
21					416	473	530	587	644	701	758			12
22					448	511	573	635	698	760	823			6
23					482	550	618	686	754	823	891			7
24						592	666	740	814	888	962			9
25						635	715	795	875	955	1036			6
26						680	766	853	939	1026	1112			5
27						726	819	913	1006	1099	1192			7
28							875	975	1075	1175	1275	1375	1475	4
29							932	1039	1146	1254	1361	1468	1575	4
30							991	1106	1220	1335	1450	1564	1679	3
31								1174	1297	1419	1541	1664	1786	1
32								1245	1376	1506	1636	1766	1896	2
33									1457	1595	1734	1872	2010	0
34											1834	1981	2127	1
35											1938	2093	2248	0
36											2044	2208	2372	1
Basis: No. Trees	15	27	41	42	45	43	33	29	23	8	4	2	0	312

Block indicates extent of basic data.
Derived from: $V = 0.30857\ D^2H + 8.14191$, for D^2L to 1060
$V = 0.24647\ D^2H + 73.92559$, for D^2L larger than 1060
Standard errors of estimate: ± 12.51 percent; ± 10.50 percent
Diameter classes full-inch; e.g. 20-inch class includes 20.0 to 20.9

Table 19.--Gross volumes in board feet International 1/4-inch Rule per square foot of basal area, Engelmann spruce in Colorado and Wyoming

Board feet inside bark
Merchantable stem excluding stump and top

Top diameter 8 inches inside bark
Stump height 1.0 foot

Diameter breast height outside bark (Inches)	Number of 16-foot logs to 8-inch top												
	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0	6.5	7.0
	Board feet												
10	70	98	127	155									
11	68	96	124	153	181								
12	66	94	123	151	179	208							
13		93	121	150	178	206	234						
14		92	120	149	177	205	233	262					
15			119	148	176	204	233	260					
16			119	147	175	204	231	253	276				
17			118	146	175	202	225	248	270				
18				146	174	198	220	243	266	288			
19				145	171	194	216	239	262	284			
20				145	168	190	213	236	258	281	303		
21					165	187	210	233	255	278	300		
22					162	185	208	230	253	275	298		
23					160	183	205	228	250	273	296		
24						181	203	226	249	271	294		
25						179	202	224	247	269	292		
26						177	200	223	245	268	290		
27						176	199	221	244	266	289		
28							197	220	243	265	288	310	333
29							196	219	242	264	287	309	332
30							195	218	241	263	286	308	331
31								217	240	262	285	307	330
32								216	239	261	284	307	329
33									238	261	283	306	328
34											283	305	328
35											282	304	327
36											281	304	327

Derived from: $V/B = 56.5768\ L + 1492.8328/D^2$, above dotted line
$V/B = 45.1907\ L + 13554.3803/D^2$, below dotted line

Diameter classes full-inch; e.g. 20-inch class includes 20.0 to 20.9

Myers, Clifford A., and Carleton B. Edminster.
1972. Volume tables and point-sampling factors for Engelmann spruce in Colorado and Wyoming. USDA Forest Serv. Res. Pap. RM-95, 23 p. Rocky Mountain Forest and Range Experiment Station, Fort Collins, Colorado 80521.

Volumes are in total cubic feet and cubic feet to a 4.0-inch top, board feet Scribner Rule to 6-inch and 8-inch tops, and board feet International ¼-inch Rule to 6-inch and 8-inch tops. Tree heights are in feet and numbers of logs. Volume equations are of the form $V = a + bD^2H$.

Keywords: Tree volume tables, tree volume estimates, stand volume estimates, *Picea engelmannii*.

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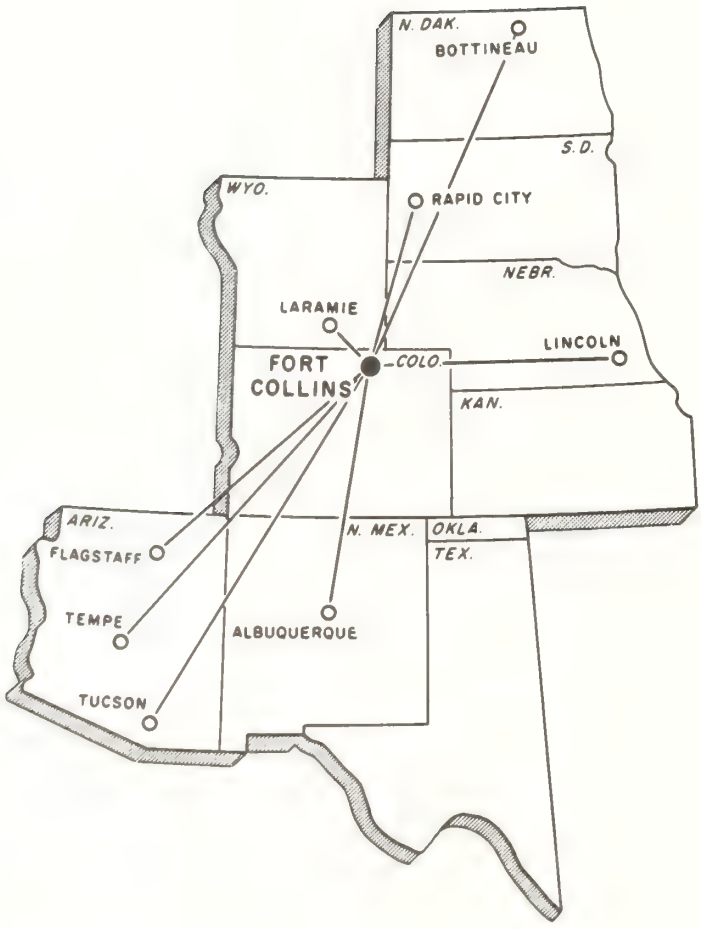
Keywords: Tree volume tables, tree volume estimates, stand volume estimates, *Picea engelmannii*.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FLOW AND CHANNEL CHARACTERISTICS OF TWO HIGH MOUNTAIN STREAMS

by Burchard H. Heede

ABSTRACT

Steps provided by logs fallen across the channel added to flow energy reduction. The streams required an additional number of gravel bars to adjust to slope. Average step length between logs and gravel bars are strongly related to channel gradient and median bed material size. More bars formed when fewer numbers of logs were available. Although these are "rushing mountain streams," most values for flow velocities ranged between 0.5 and 2.5 feet per second. Exponents of functions expressing rate of change of depth or velocity, respectively, with discharge, indicated that dynamic stream equilibrium was attained. Implications for forest management are that sanitation cuttings (removal of dead and dying trees) would not be permissible where dynamic stream equilibrium exists and bed material movement should be minimized.

Keywords: Mountain streams, hydraulic geometry, step formations, bed material movement, flood plain forest management.

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Flow and Channel Characteristics of Two High Mountain Streams

by

Burchard H. Heede, Hydraulic Engineer
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[1] *Central headquarters maintained at Fort Collins, in cooperation with Colorado State University. Research reported here was conducted while author was assigned to Fort Collins; he is now located at the Station's Albuquerque field unit, in cooperation with the University of New Mexico.*

Flow and Channel Characteristics of Two High Mountain Streams

Burchard H. Heede

Many small streams constitute the arteries
y which much of the water stored in the high
ountain snowpacks of Colorado is conveyed
the lowlands for people and industry. With
creasing demands for water, manipulation of
ie small mountain streams can be expected to
crease. Very little is known about flow and
annel characteristics of these small streams.
he acquisition of such knowledge is important
a safeguard against misuse and to assure
ean water.

Study Area

The study streams, Fool Creek and Dead-
orse Creek, lie within the Fraser Experimental
orest, approximately 50 miles west of Denver,
olorado. Both streams originate above timber-
ne at an elevation of about 11,500 feet. Chan-
el reaches studied were above 9,600 feet on
ool Creek and 9,300 feet on Deadhorse Creek.

The climate is cool, with an average yearly
mperature of about 35° F. Annual precipita-
n averages 24 inches and varies from 15 to
inches; two-thirds of the precipitation occurs
snowfall. Streamflows generally reach a min-
num in early April and peak in mid-June.
uring the record period 1952-65, the annual
ak flow of Fool Creek averaged 14.2 cubic
et per second (c.f.s.), while the largest peak
as 24.3 c.f.s. Deadhorse Creek had an average
ak of 7.8 c.f.s. and a maximum of 13.6 c.f.s.

Flow levels decrease rapidly after the spring
ak has passed. The winter low flows of both
reams generally do not carry more than 0.3
.s. Approximately 80 percent of the total
arly flow occurs between April and October.

Sediment loads are extremely small in both
reams. Average annual sediment yield for the
year period preceding this study was 297
ft^3/mi^2 from Fool Creek and 147 ft^3/mi^2 from Deadhorse Creek (Leaf 1966). This yield estimate was based on the sediment load collected in sediment basins below the study reaches.

Fool Creek is characterized by long, gentle, relatively uniform slopes, whereas on Deadhorse Creek, slopes are less uniform and somewhat steeper. The median slopes of Fool Creek and Deadhorse are approximately 26 and 36 percent, respectively.

The parent material of soils on the watersheds was derived primarily from gneiss and schist (Retzer 1962). Typical soils contain angular gravel and stone, and a small amount of silt and clay.

Long stretches of both streams are embedded in alluvium. Some reaches are lined with rock outcrops and to a lesser extent by boggy soils. All reaches have rocky bottoms. Sand and gravel typically accumulate behind barriers across the channels.

The forest, estimated to be between 250 and 400 years old, is composed of Engelmann spruce (Picea engelmanni Parry), subalpine fir (Abies lasiocarpa (Hook.) Nutt.), and lodgepole pine (Pinus contorta Dougl.). Half of the merchantable timber on the Fool Creek watershed was removed by alternate-strip clearcutting between 1954 and 1956 (Goodell 1958, Love and Goodell 1960). The primary access road on Fool Creek was located to avoid the main stream channel and to minimize soil disturbance. Timber was made accessible by spur roads spaced at approximately 400-foot intervals along the contour; the spurs were provided with adequate surface drainage and culverts at stream crossings. In 1957 spurs were seeded to grass and culverts were removed on alternate roads to reduce traffic. The forest on Deadhorse Creek is uncut, except for approximately 30 acres on the south slope, which was commercially clearcut between 1942-46.

gradients are misleading, however, since within each reach values for cumulative heights (above the bed) of gravel and log steps are between 50 and 100 percent of those of the total falls. This means that the potential energy is in part offset by the steps since below each step considerable energy is dissipated, and the flow must regain its momentum. Since, in many cases, a pronounced scour hole developed below the steps, a negative channel gradient was obtained for the slope between the steps.

Although Deadhorse Creek has a much steeper channel gradient than Fool Creek, it carries only half the sediment load. The mechanics of stream adjustment is a function of the interactions of many factors, but differences in the ratios between cumulative height of steps and total fall of bed may largely account for differences in the load characteristics of the streams.

	Ratio
FOOL CREEK	
Lower reach	0.87
Upper reach	.54
Average	.70
DEADHORSE CREEK	
Lower reach	1.01
Upper reach	.95
Average	.98

Cumulative height of steps nearly equals the total fall of the bed on Deadhorse Creek, while on Fool Creek cumulative step height is less than 75 percent of the total fall. Thus, the steepness of the channel gradient is more effectively offset by the formation of steps on Deadhorse than on Fool Creek, and less energy is available for transport of sediment on the former.

Table 2. Flow and channel characteristics of Deadhorse Creek

Cross section	Discharge (Q)	Mean velocity[1] (v)	Depth of flow: Max. (d_{max})	Depth of flow: Mean (d_m)	Bank to bank width (w)	Froude number[2] (F)	Width-depth ratio ($\frac{w}{d_m}$)	Shape factor ($\frac{d_{max}}{d_m}$)
	c.f.s.	f.p.s.	Feet					
A	2.32	1.75	0.36	0.23	5.75	2.05	25.0	1.6
	2.20	1.58	.37	.24	5.75	1.81	24.0	1.5
	2.03	1.53	.35	.24	5.62	1.75	23.4	1.5
	1.78	1.39	.35	.22	5.80	1.66	26.4	1.6
	1.57	1.21	.33	.22	5.80	1.45	26.4	1.5
B	1.94	1.49	.97	.70	1.85	1.00	2.6	1.4
	1.72	1.35	.92	.69	1.85	.91	2.7	1.3
	1.59	1.17	.90	.68	2.00	.80	2.9	1.3
	1.32	1.03	.90	.64	1.85	.70	2.7	1.3
	1.73	1.30	.84	.66	2.00	.90	3.0	1.3
	1.55	1.25	.84	.67	1.85	.86	2.8	1.3
	1.09	1.11	.77	.53	1.85	.86	3.5	1.5
C	2.36	1.06	1.01	.93	2.40	.62	2.6	1.1
	1.68	.81	.93	.85	2.45	.49	2.9	1.1
	1.95	.98	.90	.81	2.45	.61	3.0	1.1
	.63	.37	.77	.69	2.45	.25	3.6	1.1
D	.77	1.45	.25	.14	3.85	2.18	27.5	1.8
	.24	.79	.21	.16	1.90	1.11	11.9	1.3
E	.74	1.06	.48	.20	3.55	1.33	17.8	2.0

[1] Based on point velocities measured by Pygmy current meter.

[2] $F = \frac{v}{\sqrt{gd_m}}$, where g is the acceleration due to gravity.

The reduction of available energies by gravel and log steps, in combination with the roughness exerted by gravel beds and rock outcrops, is illustrated by the velocities of flow, which are indeed low for "rushing mountain streams." Mean velocities of Deadhorse Creek ranged from 0.37 to 1.75 feet per second (f.p.s.) (table) whereas velocities ranged from 0.52 to 4.85 f.p.s. on Fool Creek (table 3). Corresponding discharges were between 0.63 and 2.32 c.f.s. on Deadhorse and between 1.01 and 17.45 c.f.s. on Fool Creek. Most velocities of Deadhorse Creek fluctuated around 1 f.p.s. On Fool Creek, the value of 4.85 f.p.s. was measured only once; values usually ranged between 0.5 and 2.5 f.p.s.

Mean stream velocities are ordinarily determined from one- or two-point measurements in several vertical sections. This procedure, developed for large channels, assumes a logarithmic variation of velocity with depth. However, in turbulent, high-mountain streams the vertical velocity profiles do not resemble the logarithmic profile characteristics of larger channels. Standard depth levels for velocity measurements are therefore unrealistic for these streams.

Cumulative frequency curves of bed particle sizes for two reaches of Deadhorse Creek, typical for both streams, resemble the distribution often shown by river gravels (fig. 4). Ninety percent of the sample particles from the lower reach had a diameter of 50 mm or smaller, while 90 percent of the sample particles 800 feet upstream had diameters of 160 mm or smaller (fig. 4). This decrease in bed particle sizes in the downstream direction is characteristic of most streams, and is associated with a general decrease of the channel gradient downstream (fig. 5).

Because of the relatively steep banks and level channel bed (fig. 6), width varied very little with discharge at a station. Mean depths in Deadhorse Creek ranged between 0.14 and 0.93 foot for discharges between 0.77 and 2.36 c.f.s., and 0.20 to 1.05 feet for discharges between 0.97 and 7.14 c.f.s. in Fool Creek. Maximum depths ranged from 0.21 to 1.01 feet for discharges of 0.24 to 2.36 c.f.s. in Deadhorse Creek, and 0.27 to 1.60 feet at 0.97 to 10.30 c.f.s. in Fool Creek. These data indicate that the rapid increase of depth with discharge will lead to submergence of gravel and log steps at extreme flows. Such submergence did not occur during the study period.

If width and depth are considered together, such as in the width-depth ratio, a quantitative expression of channel shape will be obtained because relative rates of increase of width and depth are functions of channel shape. In cross sections with pure geometric shapes, the following relationships exist: in a triangular-shaped channel, the width-depth ratio remains constant with changing discharge; the width-depth ratio decreases in trapezoidal and elliptical cross sections when discharge increases; width-depth ratio decreases much more rapidly with in-

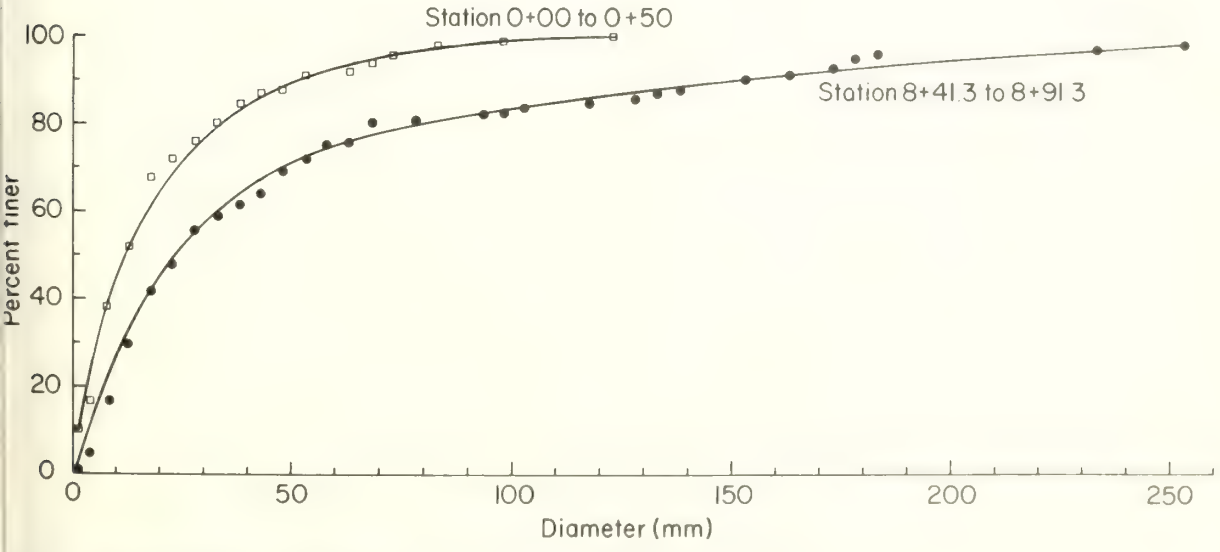


Figure 4. Bed particle size distribution for two reaches of Deadhorse Creek.

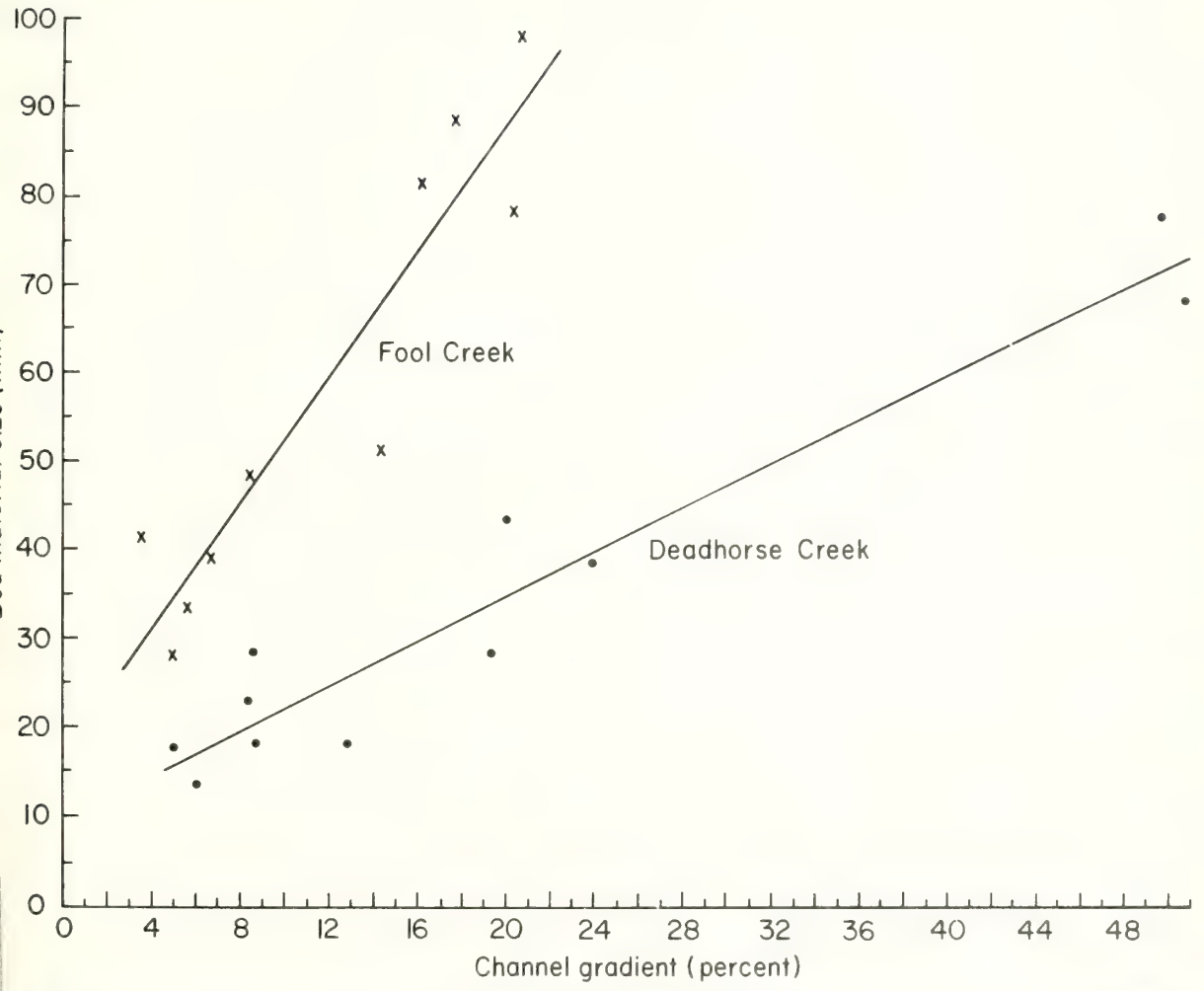
Table 3. Flow and channel characteristics of Fool Creek

Cross section	Discharge (Q)	Mean velocity[1] (v)	Depth of flow: Max. (d_{max})	Depth of flow: Mean (d_m)	Bank to bank width (w)	Water temperature	Reynolds number[2] (ℝ)	Froude number[3] (𝔽)	Width-depth ratio $\left(\frac{w}{d_m}\right)$	Shape factor $\left(\frac{d_{max}}{d_m}\right)$
	c.f.s.	f.p.s.	Feet	Feet	Feet	°F				
A	6.11	2.07	0.62	0.49	6.00			1.60	12.2	1.3
	4.75	1.78	.62	.45	6.00			1.49	13.3	1.4
	7.18	2.47	.71	.49	6.00			1.98	12.2	1.5
	5.14	1.91	.64	.45	6.00			1.60	13.3	1.4
	7.80	2.66	.64	.49	6.00			2.13	12.2	1.3
	8.44	2.33	.76	.61	6.00			1.67	9.8	1.3
	6.52	2.08	.75	.52	6.00			1.62	11.5	1.4
	8.65	2.33	.82	.62	6.00			1.66	9.7	1.3
	3.81	1.91	.73	.32	6.30	37	34,500	1.89	19.7	2.3
	4.15	2.09	.68	.32	6.30	42	41,300	2.07	19.7	2.1
	3.02	1.76	.65	.27	6.30	44	30,300	1.90	23.3	2.4
	1.65	1.15	.59	.23	6.30	45	17,200	1.35	27.4	2.6
	2.56	1.43	.66	.28	6.30	43	25,200	1.52	22.5	2.4
	1.94	1.51	.53	.22	5.90	47	22,300	1.81	26.8	2.4
B	17.45	4.85	1.16	.90	4.00			2.87	4.4	1.3
	11.04	3.76	1.07	.84	3.50			2.30	4.2	1.3
	5.80	2.24	1.05	.74	3.50			1.46	4.7	1.4
	8.38	2.51	1.29	.84	4.00			1.54	4.8	1.5
	7.76	2.27	1.33	.86	4.00			1.37	4.7	1.6
	2.51	1.27	.93	.53	3.75	37	38,000	.98	7.1	1.8
	2.17	1.37	.77	.43	3.70	45	38,300	1.17	8.6	1.8
	1.56	1.22	.66	.35	3.70	45	27,700	1.16	10.6	1.9
	2.04	1.24	.80	.45	3.70	43	35,100	1.04	8.2	1.8
	1.31	1.06	.73	.34	3.70	47	24,200	1.02	10.9	2.2
C	9.40	2.51	1.25	1.03	3.65			1.39	3.5	1.2
	3.06	1.43	.86	.61	3.50	40	52,200	1.03	5.7	1.4
	1.61	.96	.71	.51	3.30	45	31,800	.75	6.5	1.4
	1.13	.79	.64	.43	3.30	45	21,400	.68	7.7	1.5
	1.58	.97	.70	.49	3.30	43	29,900	.78	6.7	1.4
	1.01	.72	.68	.42	3.30	46	20,000	.62	7.9	1.6
D	9.69	1.89	1.20	1.00	5.15			1.06	5.2	1.2
	8.91	1.81	1.09	.95	5.15			1.04	5.4	1.2
	3.21	.89	.86	.70	5.15	38	35,600	.60	7.4	1.2
	2.72	.90	.75	.59	5.15			.60	8.7	1.3
	2.52	.82	.84	.60	5.15	37	27,800	.59	8.6	1.4
	1.93	.74	.72	.51	5.15	46	25,000	.58	10.1	1.4
	1.43	.63	.60	.44	5.15	46	18,400	.53	11.7	1.4
	1.71	.80	.63	.41	5.15	46	21,700	.70	12.6	1.5
E	10.30	2.09	1.60	.92	5.35			1.22	5.8	1.7
	8.35	1.76	1.54	.89	5.35			1.05	6.0	1.7
	2.76	.91	1.32	.57	5.30	37	32,000	.68	9.3	2.3
	2.75	.84	1.30	.61	5.30	42	31,600	.52	8.7	2.1
	2.27	.83	1.10	.75	3.65			.54	4.6	1.5
	1.48	.73	1.01	.56	3.65	37	23,100	.55	6.5	1.8
	1.10	.58	1.00	.52	3.65	46	20,000	.45	7.0	1.9
	1.18	.61	1.00	.53	3.65	45	21,000	.47	6.9	1.9
	1.01	.52	.96	.63	3.10			.34	4.9	1.5
F	6.52	2.82	0.70	0.55	4.20			2.13	7.6	1.3
	4.91	2.59	.56	.45	4.20			2.17	9.3	1.2
	3.05	2.22	.46	.33	4.20	38	41,900	2.17	12.7	1.4
	1.59	1.91	.33	.26	3.20			2.10	12.3	1.3
	1.24	1.88	.28	.21	3.20	46	26,100	2.30	15.2	1.3
	.97	1.64	.27	.20	3.00	45	21,300	2.06	15.0	1.4
	1.04	1.68	.28	.21	3.00	46	23,400	2.06	14.3	1.3
G	7.14	2.39	1.23	1.05	2.85			1.31	2.7	1.2
	5.49	2.04	1.29	.94	2.85			1.18	3.0	1.4
	1.66	.99	.85	.62	2.70	39	35,900	.71	4.4	1.4
	2.15	1.14	.85	.70	2.70	41	47,000	.76	3.9	1.2
	1.23	.87	.72	.50	2.85			.69	5.7	1.4
	.84	.70	.57	.38	3.15	46	39,000	.64	8.3	1.5
	.74	.61	.65	.44	2.75	45	17,400	.52	6.3	1.5
	.78	.60	.63	.46	2.85	46	18,300	.50	6.2	1.4

[1] Based on point velocities attained by Pygmy current meter.

[2] $\mathbb{R} = \frac{vd_m}{\nu}$, where ν is the kinematic viscosity in ft.^{2}/second.

[3] $\mathbb{F} = \frac{v}{\sqrt{gd_m}}$, where g is the acceleration due to gravity taken as 32.2 ft./sec.^{2}.



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$$w/d = rQ^s$$

ere w/d is the width-depth ratio, Q is the charge, and r and s are numerical coeffi-nts. The value of s, the slope of the line ulting from a log-log plot of the equation, expresses the relative rate of decrease of the ratio with increasing discharge. An example from three stations is plotted in figure 7.

Channel shape can also be approximated by use of the shape factor, the quotient of maximum depth divided by mean depth. If such true geometric shapes as triangles, parabolas, and rectangles are considered, the respective shape factors would be 2.0, 1.5, and 1.0. The most effective hydraulic shape would be a semicircle, which normally does not exist in natural streams.

The last column of table 2 indicates that each cross section at Deadhorse Creek has a relatively uniform shape factor through the range of measured discharges. The table also shows that the shape factor is close to parabolic at station A, while nearly rectangular at

Table 3. Flow and channel characteristics of Fool Creek

Cross section	Discharge	Mean velocity[1]	Depth of flow		Bank to bank width	Water temperature	Reynolds number[2]	Froude number[3]	Width-depth ratio	Shape factor
			Max.	Mean						
			(d_{max})	(d_m)	(w)		(ℝ)	(𝔽)	$\left(\frac{w}{d_m}\right)$	$\left(\frac{d_{max}}{d_m}\right)$
	c.f.s.	f.p.s.	- - - - - - Feet - - - - - -			°F				
A	6.11	2.07	0.62	0.49	6.00			1.60	12.2	1.3
	4.75	1.78	.62	.45	6.00			1.49	13.3	1.4
	7.18	2.47	.71	.49	6.00			1.98	12.2	1.5
	5.14	1.91	.64	.45	6.00			1.60	13.3	1.4
	7.80	2.66	.64	.49	6.00			2.13	12.2	1.3
	8.44	2.33	.76	.61	6.00			1.67	9.8	1.3
	6.52	2.08	.75	.52	6.00			1.62	11.5	1.4
	8.65	2.33	.82	.62	6.00			1.66	9.7	1.3
	3.81	1.91	.73	.32	6.30	37	34,500	1.89	19.7	2.3
	4.15	2.09	.68	.32	6.30	42	41,300	2.07	19.7	2.1
	3.02	1.76	.65	.27	6.30	44	30,300	1.90	23.3	2.4
	1.65	1.15	.59	.23	6.30	45	17,200	1.35	27.4	2.6
	2.56	1.43	.66	.28	6.30	43	25,200	1.52	22.5	2.4
	1.94	1.51	.53	.22	5.90	47	22,300	1.81	26.8	2.4
B	17.45	4.85	1.16	.90	4.00			2.87	4.4	1.3
	11.04	3.76	1.07	.84	3.50			2.30	4.2	1.3
	5.80	2.24	1.05	.74	3.50			1.46	4.7	1.4
	8.38	2.51	1.29	.84	4.00			1.54	4.8	1.5
	7.76	2.27	1.33	.86	4.00			1.37	4.7	1.6
	2.51	1.27	.93	.53	3.75	37	38,000	.98	7.1	1.8
	2.17	1.37	.77	.43	3.70	45	38,300	1.17	8.6	1.8
	1.56	1.22	.66	.35	3.70	45	27,700	1.16	10.6	1.9
	2.04	1.24	.80	.45	3.70	43	35,100	1.04	8.2	1.8
	1.31	1.06	.73	.34	3.70	47	24,200	1.02	10.9	2.2
C	9.40	2.51	1.25	1.03	3.65			1.39	3.5	1.2
	3.06	1.43	.86	.61	3.50	40	52,200	1.03	5.7	1.4
	1.61	.96	.71	.51	3.30	45	31,800	.75	6.5	1.4
	1.13	.79	.64	.43	3.30	45	21,400	.68	7.7	1.5
	1.58	.97	.70	.49	3.30	43	29,900	.78	6.7	1.4
	1.01	.72	.68	.42	3.30	46	20,000	.62	7.9	1.6
D	9.69	1.89	1.20	1.00	5.15			1.06	5.2	1.2
	8.91	1.81	1.09	.95	5.15			1.04	5.4	1.2
	3.21	.89	.86	.70	5.15	38	35,600	.60	7.4	1.2
	2.72	.90	.75	.59	5.15			.60	8.7	1.3
	2.52	.82	.84	.60	5.15	37	27,800	.59	8.6	1.4
	1.93	.74	.72	.51	5.15	46	25,000	.58	10.1	1.4
	1.43	.63	.60	.44	5.15	46	18,400	.53	11.7	1.4
	1.71	.80	.63	.41	5.15	46	21,700	.70	12.6	1.5
E	10.30	2.09	1.60	.92	5.35			1.22	5.8	1.7
	8.35	1.76	1.54	.89	5.35			1.05	6.0	1.7
	2.76	.91	1.32	.57	5.30	37	32,000	.68	9.3	2.3
	2.75	.84	1.30	.61	5.30	42	31,600	.52	8.7	2.1
	2.27	.83	1.10	.75	3.65			.54	4.6	1.5
	1.48	.73	1.01	.56	3.65	37	23,100	.55	6.5	1.8
	1.10	.58	1.00	.52	3.65	46	20,000	.45	7.0	1.9
	1.18	.61	1.00	.53	3.65	45	21,000	.47	6.9	1.9
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	1.59	1.91	.33	.26	3.20			2.10	12.3	1.3
	1.24	1.88	.28	.21	3.20	46	26,100	2.30	15.2	1.3
	.97	1.64	.27	.20	3.00	45	21,300	2.06	15.0	1.4
	1.04	1.68	.28	.21	3.00	46	23,400	2.06	14.3	1.3
G	7.14	2.39	1.23	1.05	2.85			1.31	2.7	1.2
	5.49	2.04	1.29	.94	2.85			1.18	3.0	1.4
	1.66	.99	.85	.62	2.70	39	35,900	.71	4.4	1.4
	2.15	1.14	.85	.70	2.70	41	47,000	.76	3.9	1.2
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[1] Based on point velocities attained by Pygmy current meter.

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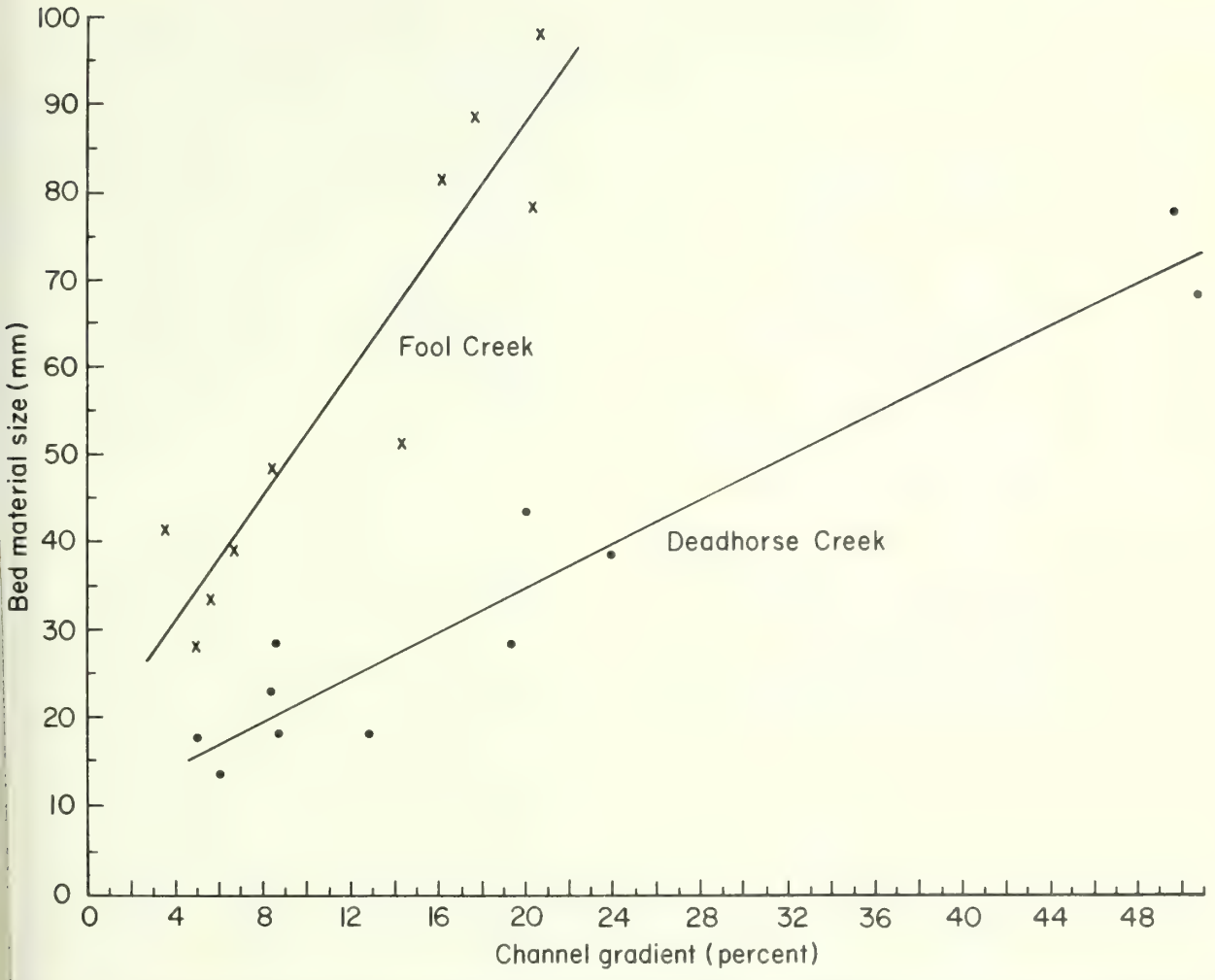

Figure 5. Relationship between median bed material size and channel gradient for Fool Creek and Deadhorse Creek.

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When the width-depth ratio is expressed as a function of discharge at a station, a simple power function is derived:

$$w/d = rQ^s$$

where w/d is the width-depth ratio, Q is the discharge, and r and s are numerical coefficients. The value of s, the slope of the line resulting from a log-log plot of the equation, expresses the relative rate of decrease of the ratio with increasing discharge. An example from three stations is plotted in figure 7.

Channel shape can also be approximated by use of the shape factor, the quotient of maximum depth divided by mean depth. If such true geometric shapes as triangles, parabolas, and rectangles are considered, the respective shape factors would be 2.0, 1.5, and 1.0. The most effective hydraulic shape would be a semicircle, which normally does not exist in natural streams.

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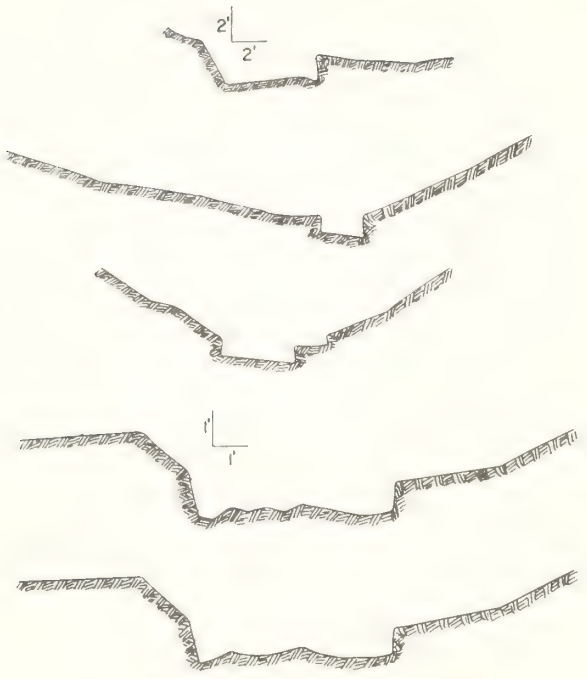


Figure 6. Typical channel cross sections for Deadhorse Creek (upper three) and Fool Creek (lower two).

station C. To verify shapes, the cross sections must be plotted because a variety of unusual sections can have the same shape factor.

Discharge measurements at Fool Creek had a larger range than those of Deadhorse Creek (table 3). This may be one of the reasons why the change in shape factors with changing discharge is much more pronounced at Fool Creek than at Deadhorse Creek. Increases in shape factor reflect a relative increase in the wetted perimeter, which increases roughness of flow and decreases channel efficiency. Thus, the hydraulic efficiency for the conveyance of water decreases at lower discharges. Such indications are given at Fool Creek station A where, at a discharge of 8.65 c.f.s., the shape factor was 1.3, while at a flow of 1.94 c.f.s., the shape factor increased to 2.4.

To test if the study streams behaved like larger streams, the methods developed by Leopold and Maddock (1953) for the treatment of hydraulic variables was applied. They found that hydraulic characteristics of stream channels such as depth, width, and velocity vary as some power function of the discharge as follows:

$$w = aQ^b,\ d = cQ^f,\ v = kQ^m$$

where w is the width, d is the mean depth, v is the velocity, and a, c, k, b, f, and m are numerical coefficients. Discharge is the product of cross-sectional area and mean velocity, or expressed algebraically, $Q = w \times d \times v$. Thus, $aQ^b \times cQ^f \times kQ^m = Q$, or $b + f + m = 1$, and $a \times c \times k = 1$. Since width changes very little with discharge, the slopes of the width-discharge curves would be near zero, and the respective exponent (b) would have a value close to zero. This is indicated by the sums of f and m, which are about 1.0 (table 4). The average values at a given station for f and m are 0.43 and 0.52, respectively. If the sums of f and m are compared with those derived from other streams and regions by other investigators (table 5), it appears that the Fool Creek data

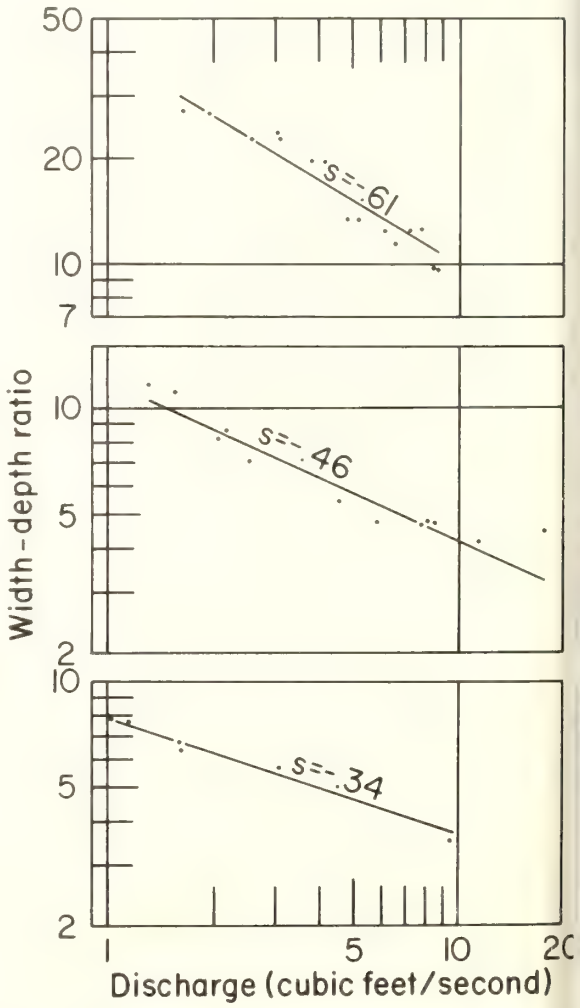


Figure 7. Typical relationships between width-depth ratio and discharge on Fool Creek.

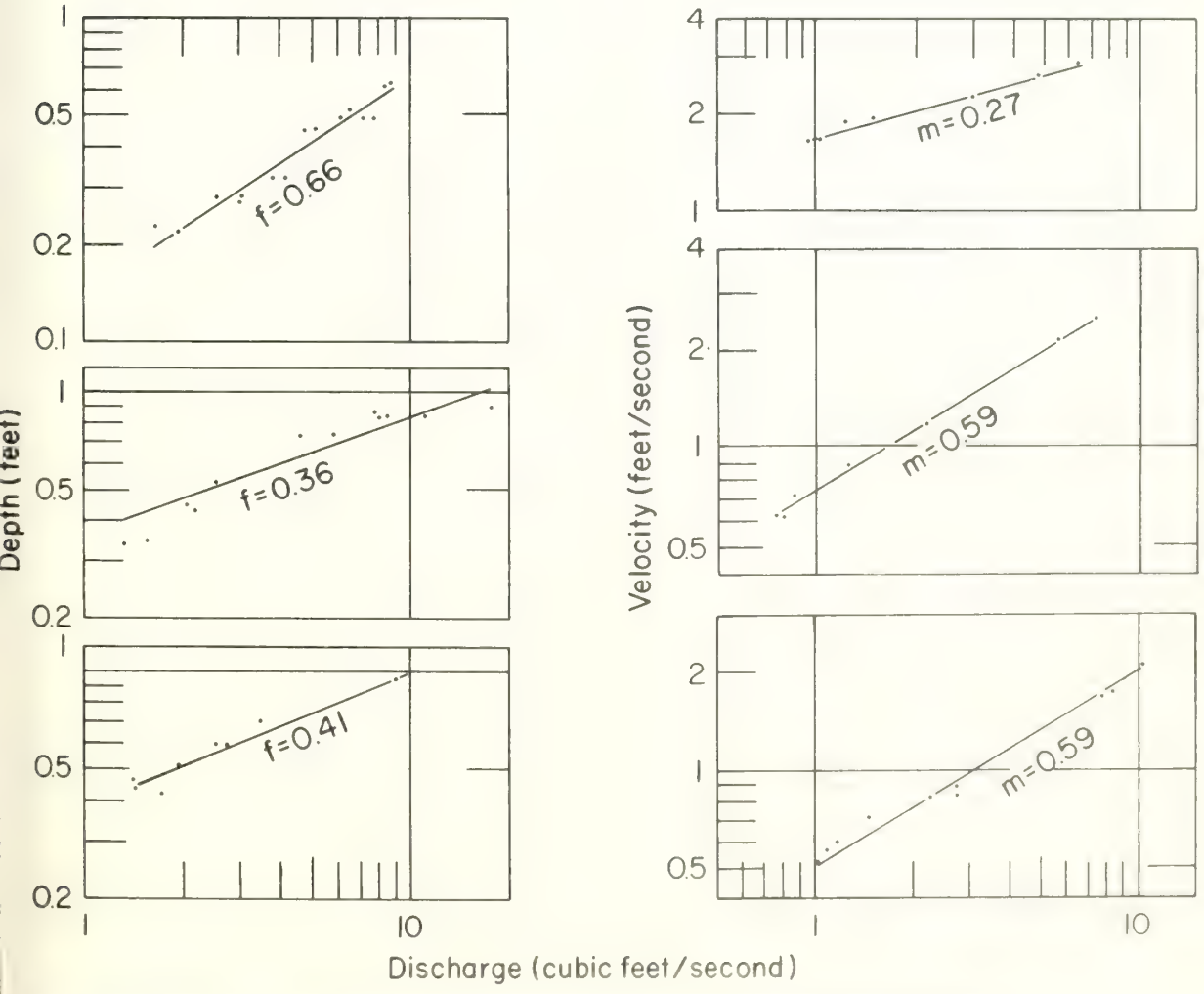
re closest to those derived from a much larger nountain stream, Brandywine Creek in Pennylvania (Wolman 1955). The relationships in gure 8, which show depth and velocity as a unction of discharge, are believed to be representative of all cross sections in Fool Creek. ischarges of Deadhorse Creek were too small n magnitude relative to instrument errors to ermit meaningful analytical treatment of the ata.

As must be expected for a small, tumbling, igh mountain stream whose bed is made up f coarse material, gravel bars, and log steps, eynolds numbers (IR) were high — between 7,000 and 52,000 (table 3) — indicating highly urbulent flows. Froude numbers (IF) in both reams showed a spread of values between a

Table 4. Relation of depth (d) and velocity (v) to discharge[1] (Q), at different cross sections of Fool Creek

Cross sections	[illegible][1]	[illegible]	[illegible]
A	$0.14\ Q^{0.66}$	[illegible]	1.04
B	[illegible]	[illegible]	1.04
C	$.41\ Q^{0.41}$	$.75\ Q^{0.59}$	.95
D	[illegible]	$.50\ Q^{0.59}$	1.00
E	$.53\ Q^{0.23}$	$.71\ Q^{0.59}$	.82
F	$.19\ Q^{0.54}$	[illegible]	[illegible]
G	$.48\ Q^{0.40}$	$.74\ Q^{0.59}$	.99

[1] Symbols explained in text.



igure 8. Depth and velocity as a function of discharge for typical cross sections on Fool Creek.

Table 5. Values of exponents[1] in the equations for the hydraulic geometry of stream channels; $d = cQ^f$ and $v = kQ^m$ (Average relations for a typical cross section)

Streams and location	f	m	f + m
Fool Creek, central Rocky Mountains	0.43	0.52	0.95
Brandywine Creek, Pennsylvania[2]	.41	.55	.96
Average values, midwestern United States[2]	.40	.34	.74
Ephemeral streams in semiarid United States	.36	.34	.70
Average of 158 gaging stations in United States[2]	.45	.43	.88
10 gaging stations on Rhine River, Europe[2]	.41	.43	.84

[1] Symbols explained in text.
[2] From Leopold, Wolman, and Miller (1964), p. 244.

few tenths and 2.9. The combined effect of viscosity and gravity (that is, considering the Reynolds number and the Froude number for a given flow) produced the following regimes of flow in Fool Creek: supercritical-turbulent, critical-turbulent, and subcritical-turbulent. Due to its unstable stage, the critical-turbulent regime may better be designated as transitional range because, at a Froude number of unity (critical), the flow will either go into a subcritical or supercritical state, or may fluctuate between both.

Water temperatures showed quite pronounced diurnal fluctuations during the summer months (fig. 9) and were directly related to air temperatures. In spite of heavy shading of the streams by relatively dense stands of trees, lag times between peak temperatures of air and water were practically nil. Temperatures increased from 36°F at 6:00 a.m. to 43°F at 1:00 p.m. on July 12.

Discussion

Detailed investigations of the longitudinal profiles showed that a great number of gravel bars and logs crossed the channel. The logs accumulated gravel and thus formed steps. Since step spacing between the logs did not change within individual channel reaches, the remaining adjustment of the streams to slope was achieved by gravel bar formation. Step length decreased with increasing channel gradient and increasing median bed material size. The cumulative height of steps formed by logs and gravel bars nearly offset the total fall of Deadhorse Creek, and approached 75 percent of the fall of Fool Creek. Bars and logs together provided an average of 7.7 and 5.4 energy dissipators for 50 feet of channel on Deadhorse and on Fool Creek, respectively.

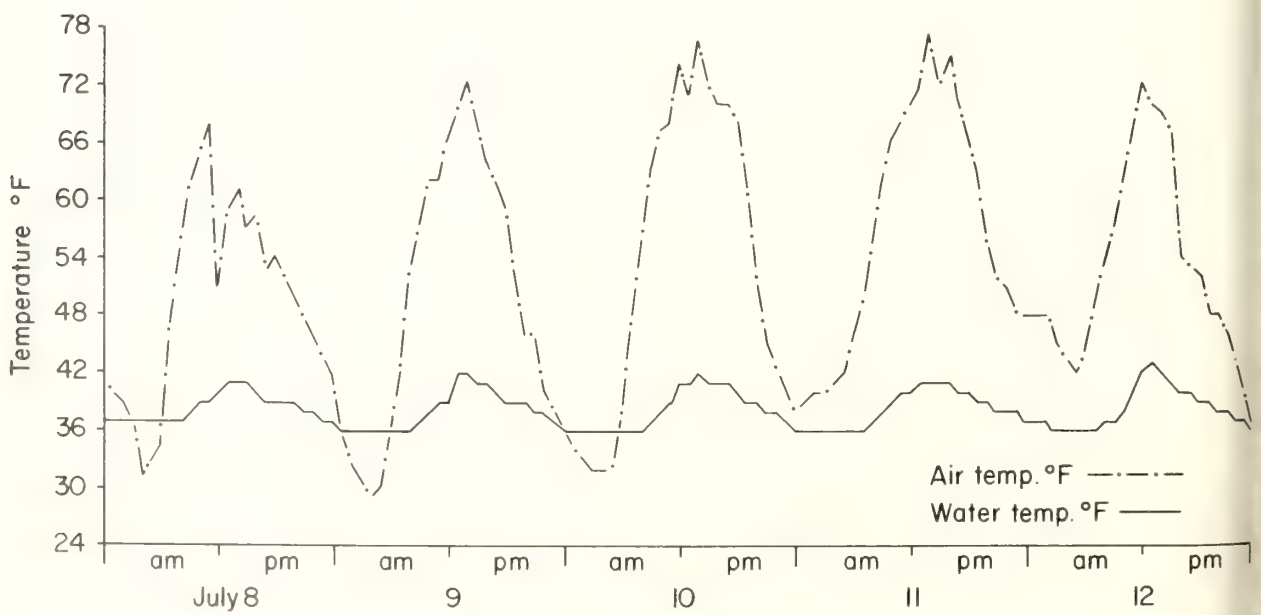


Figure 9. Daily courses of air and water temperatures at Fool Creek.

Combined with the roughness of the gravel bed, as well as other hydraulic components such as discharge, width, and slope, these energy dissipators led to relatively low velocities; most values ranged between 0.5 and 2.5 f.p.s. The average channel gradients of the reaches of the "rushing mountain streams" were 0.08 and 0.22.

Submergence of the steps would greatly reduce their effectiveness for energy reduction, and the present equilibrium of the streams, as will be discussed below, could be upset. Yet, based on 13 years of record, high flows that could lead to structural submergence occurred rarely.

When considering logs in the hydraulic geometry of small streams such as Deadhorse Creek and Fool Creek, an important contrast to gravel bars must be noted. Gravel bars are the result of stream action. They are "flexible structures" that change with flows (Kellerhals 1966). Log steps are inflexible structures if not washed out, reoriented by high flows, or rotted with time. Gravel accumulates and secures them in place. Only four locations could be found in both streams where logs had been washed out; it appeared that during flood stages the logs forced the flow around the structures and thus eroded their anchorage to one original channel bank. No evidence could be found that a gravel bar forced the flow out of its bed. Several years of record indicated only a few flows with possible higher than bankfull stages at the steps. Reorientation of logs that had fallen across the channel could not be verified, because many logs fell originally at different angles to the channel. Rotting led to loss of original height of log steps in some cases, and to breakage and loss of steps in others. Rotting appeared to be very slow.

Sediment load, normally a very important hydraulic parameter, was ignored in this investigation because the sediment yield was very small in both streams. This yield is derived mainly from a few extreme peak flows, but one occurred during the study periods.

Changes in width were minor due to rectangular channel cross sections. Cross sectional shape was expressed by the width-depth ratio and shape factor. The latter indicated loss of channel efficiency for conveyance of low flows, a fact which can be noticed by the casual observer. Within the range of flows experienced during the study, energy dissipation due to gravel and log steps as well as roughness of gravel beds and rock outcrops increased with decreasing discharge.

Reynolds and Froude numbers were in the expected range for tumbling, small mountain streams. However, in spite of heavy shading, the course of daily water temperatures was directly related to that of air temperatures. Water temperatures had a daily amplitude of up to 7°F during the middle of July.

The range of values of the exponents for the depth and velocity functions was relatively small. This indicates a certain degree of uniformity in the behavior of the hydraulic variables from station to station, which may be interpreted as an indication that Fool Creek had attained dynamic equilibrium. Discharges of Deadhorse Creek were too small during the study period to permit meaningful calculations. The dynamic equilibrium concept implies both stability and the ability to adjust; the term equilibrium can be interchanged with that of grade. But since many variables are involved in the channel-forming process that complicate any delineation of cause-and-effect relations, oversimplification must be avoided. However, Leaf (1966), in a study on sediment yield, also concluded that Fool Creek is a stream of grade. His conclusion was based on the uniform longitudinal profile concaved toward the sky, and the very small sediment load.

The study shed some light on the influence of streamside forests on the formation of steps in small mountain channels. It was shown that the streams required additional gravel bars to adjust to slope. On Deadhorse Creek, averaging 4.8 logs per 50 feet of channel, only 37 percent of the total steps were bars while on Fool Creek, averaging 2.5 logs per 50 feet of channel, 53 percent of the steps were bars. Thus less bed material moved at Deadhorse, although it had a much steeper channel slope than Fool Creek.

What is the forest management implication of the gravel bar-log step relationship? It appears that sanitation cutting (removal of dead and dying trees) should not be practiced along small mountain streams at dynamic equilibrium; the movement of bed material in such streams should be minimized. Such equilibrium is necessary, for instance, for maintenance of spawning beds for fish.

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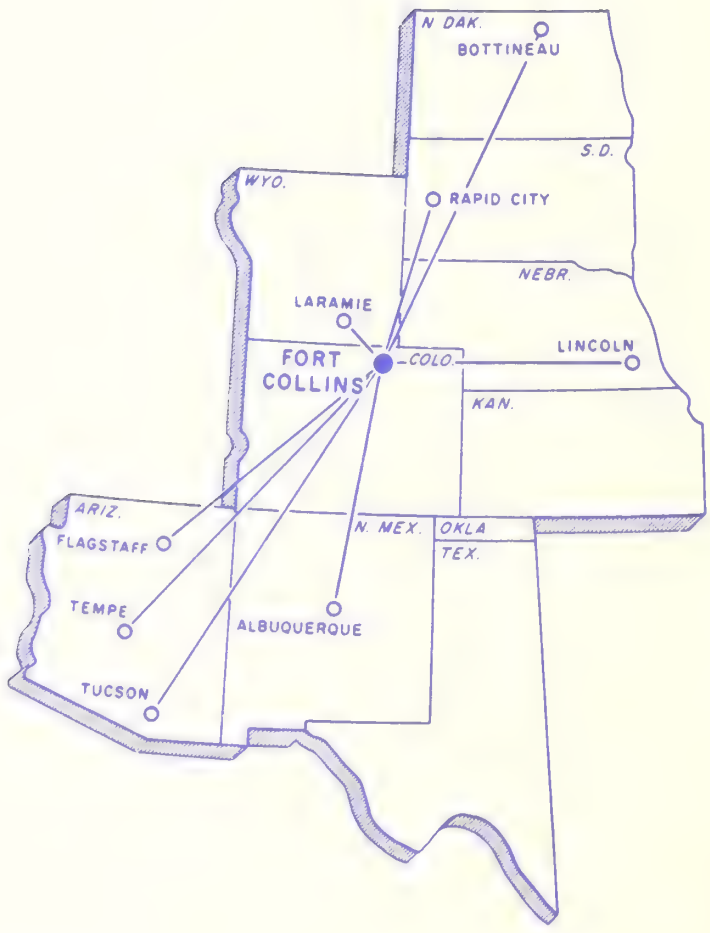
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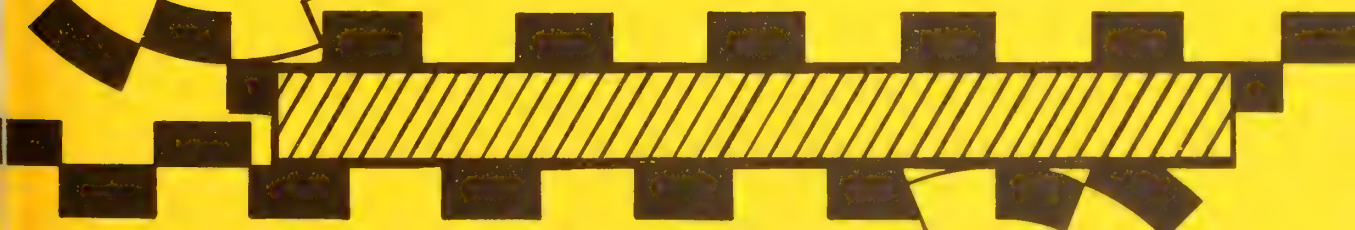
ROLL LAMINATING FIBER OVERLAYS ON LOW-GRADE PONDEROSA PINE LUMBER

by
Lincoln A. Mueller, Roland L. Barger,
Arthur Bourke, and Donald C. Markstrom



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PREFACE AND ACKNOWLEDGMENTS

Overlaying low-grade lumber with cellulose or vinyl overlays offers opportunities for producing interior and exterior products with improved appearance, utility, and market value. Recent developments in thermosetting emulsion adhesives and continuous-process roll lamination equipment have generated renewed interest in overlaid lumber products. This report describes the results of pilot tests conducted to investigate the commercial feasibility of roll laminating fiber overlays on low-grade ponderosa pine lumber.

The study included a broad analysis of potential product markets, development of roll laminating techniques, and projection of probable production costs. Additional study objectives were the development of lumber substrate quality requirements, and preliminary evaluation of potential lumber repair techniques.

This research was made possible by a technical assistance grant from the Economic Development Administration, U. S. Department of Commerce. It was conducted cooperatively by the Rocky Mountain Forest and Range Experiment Station and the Duke City Lumber Company, Albuquerque, New Mexico. The support of EDA and the cooperative effort of the Duke City Lumber Company were major factors in the success of the study. The Forest Service's Forest Products Laboratory also provided important technical guidance and consulting assistance during the study. In addition, the Wood Products Laboratory at Carbondale, Illinois, a facility of the North Central Forest Experiment Station, conducted the resawing tests for us. The authors are further indebted to the Rocky Mountain Station's marketing research staff for assistance in analyzing potential markets for overlaid products.

Abstract

Pilot plant tests were conducted with recently developed roll laminating equipment and thermosetting emulsion adhesives. Lumber that met substrate quality requirements was satisfactorily overlaid at speeds up to 180 feet per minute. Costs of overlaying, exclusive of substrate, ranged from $0.04 to $0.05 per square foot of product. A high proportion of Common grade lumber contains defects that cannot be overlaid. A second study phase found that abrasive planing (for surface defects) and urethane foam fillers (for voids) are promising repair techniques. Using selected or repaired lumber, overlaid products can be manufactured within a competitive price range. There is no strong market acceptance for such products at present, however, and aggressive market development will be needed. Commercial feasibility is currently restricted by the need for an effective automated defect repair system, and by lack of assured markets.

Keywords: *Pinus ponderosa,* forest products, lumber finishing.

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Roll Laminating Fiber Overlays on Low-Grade Ponderosa Pine Lumber

by

Lincoln A. Mueller, Roland L. Barger, Arthur Bourke, and Donald C. Markstrom

Rocky Mountain Forest and Range Experiment Station[1]

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[1]*Central headquarters is maintained at Fort Collins, in cooperation with Colorado State University. At the time research was conducted Mueller, Barger, and Markstrom were wood technologists, with Mueller and Markstrom at Fort Collins, and Barger at Flagstaff in cooperation with Northern Arizona University. Mueller is now retired, and Barger is with the U. S. Forest Service Regional Office at Missoula, Montana. Bourke was resident development engineer in charge of the pilot plant at Albuquerque, New Mexico.*

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INTRODUCTION

Lower Common grades of softwood lumber have historically been marginal products, for which demand and price are poor. The problem is particularly acute in southwestern ponderosa pine, where approximately two-thirds of the lumber produced falls in grades 3 Common and lower. For the entire Inland Region, including the Southwest, approximately half of the lumber produced is grade 3 Common or lower. Due to increasing utilization of younger residual and second-growth stands, the proportion of low Common lumber is likely to remain high. The purpose of this study was to investigate, on a pilot-plant scale, the technical and economic feasibility of upgrading low-quality ponderosa pine lumber by applying fiber overlays.

The study ultimately included two phases, one concerned with roll-laminating fiber overlays on acceptable lumber substrates, and a second concerned with methods of repairing defects that are unacceptable for overlaying in low-grade lumber. Phase I included a market analysis for overlaid products, an analysis of quality requirements for lumber substrates, and development of roll-laminating techniques. Results indicated that effective lumber repair methods were needed to make the process effective. Phase II was initiated to evaluate potential repair methods, including chemical and wood-plug patching, abrasive planing, and selective cut-up.

Basic research to identify the most promising overlay techniques and materials has been underway since 1932. These earlier efforts, some of which have been reported previously (Barger and Fleischer 1964, Fleischer and Heebink 1964, Hall 1954, Heebink 1961), showed that the overlay process had considerable potential for improving the surface characteristics of plywood and lumber. When most of this basic work was completed, however, overlaying was essentially restricted to batch process methods. The batch process imposed severe production limitations upon the overlaying of lumber, and limited the configuration of overlay and size of material that could be handled. Consequently, overlaid products received little attention until recent developments in adhesives and roll-laminating equipment made it possible to apply overlays to lumber continuously, and to wrap the overlay around the edges of the board. The roll laminator used in our study was patterned after a prototype developed in the laboratories of National Starch and Chemical Company, and was built by Eric Riebling Company, New York.[2]

Although not all the technical problems in overlaying were entirely resolved by earlier work, those familiar with the development agreed that the process was ready for pilot testing. The pilot plant was located at the Duke City Lumber Company plant in Albuquerque, New Mexico, under a cooperative agreement. The plant processes lumber received from several company mills in Arizona and New Mexico, which provided ready access to a full range of lumber grades.

PHASE I:

OVERLAID PRODUCT MARKET ANALYSIS AND MANUFACTURE

The Market Analysis

A preliminary market analysis was needed to provide a basis for selecting the most promising overlaid products for pilot-plant tests. With the assistance of a consulting firm that specializes in analyzing markets for construction products, a market screening study was conducted to:

1. Identify overlaid products that offered greatest potential.
2. Identify major competitive products.
3. Determine performance requirements and price levels for such products.
4. Estimate market size and characteristics.

[2] *Trade and company names are used for the benefit of the reader, and do not imply endorsement or preferential treatment by the U. S. Department of Agriculture.*

Product Screening and Market Investigation

The consultant, with Forest Service and industry representatives, selected 7 out of 20 potential overlaid lumber products for study: siding, fascia, shelving, molding and trim, door jambs, paneling, and stadium seats. These products held promise of being economically competitive, could meet performance requirements using a low-grade substrate material, and could capitalize on the advantages offered by an overlaid surface. Preliminary market investigations indicated that three of the seven—siding, shelving, and molding and trim—offered the greatest market potential. Major study efforts were therefore concentrated on evaluating the market potential for these three products.

Market information was obtained largely through personal interviews with representatives of relatively large builders and retail lumber dealers. A total of 179 interviews were obtained in three study areas—Chicago, Los Angeles, and Dallas-Fort Worth.

In brief, the study indicated that market opportunities may exist for a siding product capable of meeting specified performance requirements at a competitive price. Overlaid lumber siding offers sound-absorbing qualities superior to both hardboard and metal siding products and provides an excellent paint base for either on-the-job finishing, or prepriming and/or finishing. Hardboard appears to be the major competitor in the painted siding market.

Molding and trim markets are attractive, and offer significant opportunities for overlaid paintable products. A large proportion of the softwood molding and trim now sold is finger-jointed, and is either prefinished by printing or overlaying, or is painted on the job site. Grain-printed and vinyl-overlaid moldings are already widely accepted and used, and have conditioned the market to accept a paintable overlay. Builders expressed a willingness to buy and try paintable overlaid molding and trim, believing that the product would offer superior surface appearance and performance.

The market potential for overlaid shelving is less assured, primarily because alternative materials are numerous and shelving is not a particularly discriminating use. Lumber continues to dominate the shelving market, however, indicating a potential market for overlaid standard lumber widths. Because overlaid shelving can offer advantages in ease of finishing (or prefinishing), appearance, performance, and maintainability, major markets might be developed for commercial shelving and fixtures.

For all of the product markets studied, competitive products are numerous and relative technical advantages among these alternative products are often obscured by price considerations. Producers of overlaid products should therefore emphasize such inherent advantages of overlays as superior appearance, finish durability, performance, and ease of maintenance. The market analysis underscores the need for aggressive test marketing and pilot installation as an effective means of overcoming the unfamiliarity and apprehension associated with new products.

Other conclusions of general interest from the market analysis were:

1. The concept of overlaid lumber products is generally acceptable, and even attractive to many potential users if the products offer performance or price advantages over present products.
2. The color of the overlay was found to be important to the trade, even if the product is to be painted after installation. White or light-colored overlays have greater sales appeal, and are more compatible with a full range of finish colors. Priming is considered desirable over naturally dark overlay materials such as vulcanized fiber.
3. Primed and unfinished sidings presently have greater builder acceptance than prefinished products, because they require less care in handling and installation and can be finished in any color desired. Builders reacted favorably to the good paint base offered by overlays.
4. Markets for lumber siding have declined severely in the past decade, with major competitors being hardboard and aluminum. Overlaid siding can offer some of the advantages of these materials—good finishing base, appearance, and maintainability—while providing the ease of installation, strength, and insulating qualities of a solid wood product.

Limitations and Scope

The market investigation was a broad screening study to identify products and markets offering greatest promise. The conclusions are consequently subject to certain limitations. Only lower Common grades of ponderosa pine lumber were considered as substrates, except for molding and trim products. All samples used in the marketing study were overlaid with vulcanized fiber, a blue-gray product, without benefit of pre-priming. Lighter colored overlays or a primed overlay would be expected to receive a more enthusiastic response for most uses. The study was also limited to three major

narket areas—Chicago, Dallas-Fort Worth, and os Angeles—and was largely restricted to uilding products suitable for distribution hrough retail lumber dealers. The conclusions eached do not necessarily apply to products nade with better quality substrates, to smaller narkets or markets in other regions of the ountry, or to products designed for remanuacturing uses.

The study also considered only products (1) or which overlaying was known to be techically feasible with currently available overays, adhesives, and techniques, and (2) which ould be marketed in sufficient volume to aborb the production of a number of mills. While his broad approach to utilizing large volumes f low-grade lumber may not appear immediately promising, there is a strong possibility hat individual firms can develop attractive ocalized or regional markets for specific proucts, capitalizing on their established sales rganization and clientele.

Selection of Overlays and Adhesives

umber Overlays

Overlays for lumber must have some ca-acity to shrink and swell with dimensional hanges in the substrate. Potential lumber verlays include vulcanized fiber, parchments, nd acrylic and/or phenolic reinforced papers.

Five-mil vulcanized fiber has been used most xtensively in lumber overlay investigations, nd was used in all pilot production runs to stablish overlaying costs and standard operting procedures. Because considerable performnce information is available for 5-mil vulcanized ber, it was also used as a standard against hich performance of other overlays was dged.

Ten-mil vulcanized fiber was used in limited sts to evaluate the effectiveness of heavier verlays in covering defects. The overlay exibited superior bridging and hiding effectiveess, but because of its stiffness and springback ndency, it could not be successfully wrapped ith presently available adhesives. The heavier verlay may afford some advantages where wrap not essential and the product can justify the ore expensive overlay.

Parchment overlays ranging from 1½ to 5 ils (including bleached-unbleached and filled-nfilled variations) were also evaluated. The 1½-il parchment was difficult to handle due to high hygroscopicity and low wet strength. Parchments from 2½ to 5 mils thick performed satisfactorily. Compared to 5-mil vulcanized fiber, the heavier parchments afford some advantages in cost and adaptability to roll laminating. The durability of finishes on parchment is subject to question, however, and resistance to substrate defect stresses is low. Parchments also allow greater showthrough of defects and stains on the substrate, which could create some objectionable market reaction.

A variety of other overlays ranging from 4 to 20 mils were found to perform less favorably than vulcanized fiber or parchment. Brief trial runs were also made with printed vinyls, which roll laminated satisfactorily. Vinyls are suitable for interior use only, however, and therefore have limited application.

Roll-laminating Adhesives

The roll-laminating process depends on the use of thermosetting adhesives with specific operating characteristics. Cross-linking polyvinyl acetate adhesives were found to perform most satisfactorily. Several formulas were tested, with no single formula having a clearcut superiority over others. Difficulty was experienced in operating with any of the available adhesive formulations at in-plant temperatures below 45°F. and above 105°F. The ultimate selection of an adhesive formula for a particular roll-laminating operation depends on the equipment and overlay material to be used.

Selection of Lumber Substrate

Much early study effort was required to define the types and extent of defect allowable in overlay stock selected from Common lumber grades. Overlays of the type being investigated cannot successfully span voids of any consequence, and will not perform adequately over rough grain and skip. The number and severity of such defects increases gradually as lumber grade decreases.

Development of Roll-laminating Grade

Major objectives of lumber evaluation work were to determine the proportion of overlayable lumber obtainable from each commercial grade, and to establish realistic criteria for an overlayable lumber grade. Approximately 100,000

board feet of lower Common grade lumber was examined in detail and regraded for roll laminating trial runs. Defects in each board were recorded in numerical code on a portable punch-card system. Recorded information included defect types, number, severity, and—to some extent—location in the board. Later observations of performance of the board as a substrate could then be keyed back to the type or severity of defect involved.

Through trial and error, testing, and observation of substrate performance in repeated laminator runs, allowable limits of defect in overlay stock were progressively better defined. These limits have been incorporated into an "overlayable lumber grade" (table 1).

Table 1.--Specifications for overlayable lumber grade[1]

Defect	Allowable limits	Not allowable
Knots	All tight, smooth knots Firm, smooth, encased knots	Loose, decaved, split, fractured, or rough encased knots
Knotholes	1/4 inch or less	All others
Manufacturing defects	Chipped grain Raised grain Slight torn grain (1/32" max.)	Loosened or separated grain Skip Handling damage (dog marks, strap crush, etc.)
Decay	Firm, without voids	All others
Holes, insect, etc.	1/4 inch or less	All others
Checks	Surface checks	All others
Pitch and bark pockets	Smooth, without voids	All others
Compression wood	None allowed	--
Shake	None allowed	--
Pith	None allowed	--
Splits	Short splits, end	All others
Wane	Equivalent to eased edge	All others
Warp:		
Bow	Very light[2]	All others
Crook	Light[2]	All others
Cup	Very light[2]	All others
Twist	Very light[2]	All others
Moisture content	10 percent average, with variation not to exceed ± 2 percent	All others

[1] Summary description of grade: Allowed--All soild and smooth defects regardless of size; light rough or torn grain if limited in depth and area. Not allowed--Voids, severe splits, checks, skips, and warp.

[2] As defined by Western Wood Products Association (WWPA) standard grading specifications.

Recovery from Common Grades

Varying quantities of lumber in all Common grades may meet roll-laminating grade specifications, but the proportion generally declines as the lumber grade drops. The lower grades of lumber allow more defects that are of severe consequence in roll laminating. For defects such as unsound knots and knotholes, however, differences between grades are largely in defect size rather than frequency of occurrence, and affect about the same proportion of boards in grade 3 as grade 4.

To obtain a more conclusive estimate of the volume of lumber suitable for roll laminating, lumber representative of grades 3, 4, and 5 Common was inspected and regraded (table 2). The sample lumber was selected and graded at three widely separated mills, to minimize effects of defect peculiar to a mill or geographic area.

Table 2.--Recovery of overlayable grade lumber from Common lumber at three southwestern mills

Common lumber grade	Acceptable overlay stock	Unacceptable	
		Repairable[1]	Nonrepairable[2]
		Percent	
3	24	67	9
4	8	59	33
5	0	14	86

[1]Defects that could be repaired with plugs, synthetic fillers, or similar techniques.

[2]Defects of type, size, or number that exceed practical limits of repair except by cut-up.

Overlaid Product Manufacture

Roll-laminating Equipment

The roll laminator (fig. 1) obtained for the study applies adhesive-coated overlay materials, heated to a precise tack point, to lumber as it

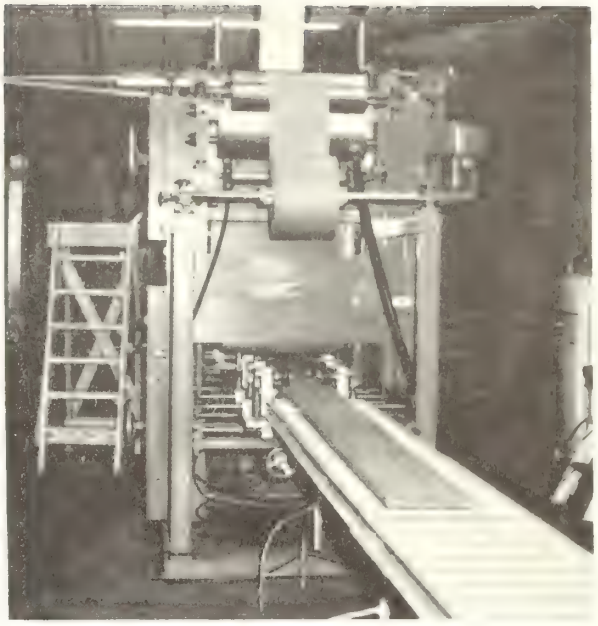


Figure 1.--The roll laminator was developed to continuously laminate fiber overlays to lumber substrates.

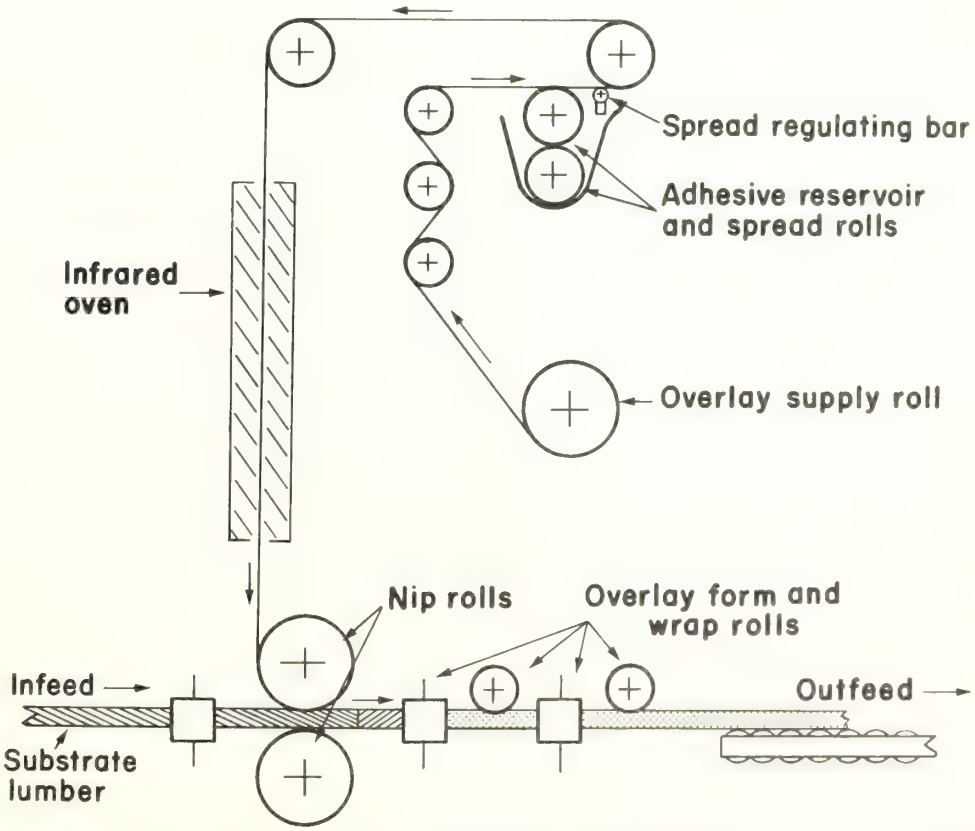


Figure 2.--A schematic drawing of the roll laminator illustrates how fiber overlay material, adhesive, and lumber are brought together in proper sequence.

passes through nip rolls. The laminator provides the coordinated mechanical systems necessary to feed overlay material, spread adhesive, tackify adhesive, feed lumber, and apply and wrap the overlay on the substrate (fig. 2). Adhesive is picked up from a supply trough by conventional spreader rolls. Paper is fed across the glue spreader roll and spread regulating bar. The adhesive-coated paper then passes through a bank of infrared heaters where it is dried to the proper tack, and is passed to the main nip roll. Lumber passes through infeed alinement rolls, through the main nip roll where the overlay is applied, and then through successive pairs of wrap rolls (fig. 3). The wrap rolls are mounted on a floating carriage to allow compensating movement for variation between boards. The laminator regulates adhesive spread, overlay web tension, heater temperature, and feed rate.

Major modifications to the basic machine included a power infeed system and a brush and vacuum lumber cleaning unit in the infeed line. An adhesive pump system was added to supply adhesive to the overhead trough, and an overhead hoist was installed to facilitate handling rolls of overlay material.

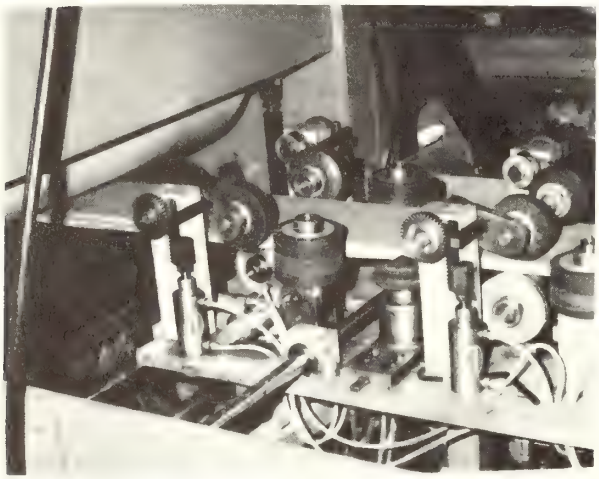


Figure 3.--The outfeed end of the roll laminator contains the roller system that wraps an overlay around the edges of the board.

Pilot Test Production Runs

Products manufactured in the pilot plant included overlaid 4/4 lumber of various widths, bevel siding, stadium seat stock, and window and door casing stock. In general, both product quality and rate of production were satisfactory for all of these products.

For beveled siding, 5/4 Common lumber was overlaid on both sides; one face and edge were overlaid on each of two passes through the laminator. The material was then resawn to a standard bevel siding pattern. Although precut bevel siding stock can be overlaid in the laminator, substantial mechanical modifications are required. Double-overlaying and resawing 5/4 flat stock is more convenient, providing damage to the overlay during resawing can be minimized. Bevel resawing lower grade knotty lumber can also be complicated by knots chipping, shattering, or deflecting the saw beyond allowable tolerances. Trials on unoverlaid lumber with a 30-inch standard bandsaw did not reveal any serious problems, however.

Stadium seat stock was produced without difficulty by applying the overlay to the top face, and wrapping around both edges of 8/4 stock. A special guide was installed on the laminator to help form the overlay around the added thickness.

Production of door and window casing stock was limited to relatively simple profiles at least 3½ inches wide, the minimum width for the pilot plant laminator. Because much of the lumber commonly used for trim items is of higher grade, such production would not contribute directly to the solution of the low-grade lumber problem. It could complete an overlaid siding or paneling system, however.

All production runs were made at machine speeds of 90 to 130 lineal feet per minute. The minimum practical speed for operation of the roll laminator is approximately 60 feet per minute. Short feasibility runs were made at speeds as high as 180 feet per minute.

Process Quality Control

A number of process conditions are potentially variable. Fluctuations in adhesive spread and heater temperature, lag or overshoot in control responses, and variation in substrate temperature and moisture content may affect product quality. Quality of the initial adhesive bond must be judged at frequent intervals during the production process, as a basis for making equipment adjustments. Later tests are needed to evaluate the quality of the cured glue bond.

Two quality tests developed by the Forest Products Laboratory were used extensively. The first employs a vacuum cup device to apply a lifting force to the overlay on any selected surface area (fig. 4). The device is particularly useful in testing bond quality over defects. The second is a variation of the established vacuum-

soak test procedure (initial vacuum, followed by half-hour soak, and subsequent ovendrying), to simulate a variety of use conditions.

Other quality control tests developed include a peel test and a whole-board soak test. As the name implies, the peel test consists of stripping the overlay from a board surface by hand and noting the fiber failure. This is perhaps the most useful test of initial adhesive bond, although it requires an experienced observer. Peel strength can be observed at frequent intervals during production as a quick check on bond adequacy. In the whole-board soak test, glue lines are subjected to all the interacting stresses that occur with major moisture content changes in the substrate. Results of exposure tests conducted to date correlate better with the whole-board soak test than with any other quality tests.

Achieving a desired level of product quality requires considerable experience, training, and attention to detail by the operator. The basic requirements for implementing quality control are:

1. Cleanliness of equipment, substrate, overlay, and adhesive.
2. Positive control of overlay tension.
3. Uniform spread of adhesive.
4. Accurate temperature control, coupled with precise speed control.

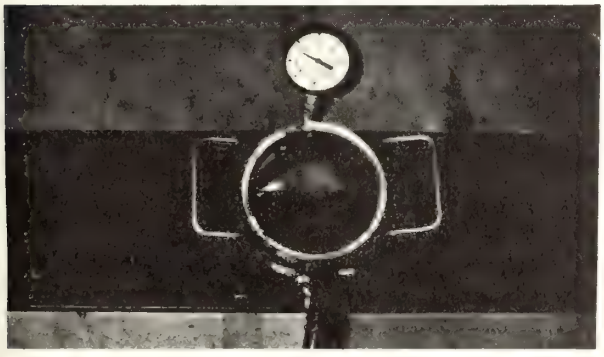


Figure 4.--A suction device provides a quick evaluation of initial overlay-to-substrate glue bond quality.

Production Costs

True costs of production are difficult to derive from pilot plant operations, since auxiliary equipment and conditions of production are usually somewhat primitive. Nevertheless, pilot plant costs can provide a factual basis for judging full production costs, and can focus attention on the relative importance of the various production factors.

Total costs of production include costs of the overlay and substrate, direct processing material and labor costs, and indirect equipment and facility costs. Only direct material and labor use per unit of production can be observed and measured during pilot plant operations; indirect costs and, to some extent, substrate costs must be estimated on the basis of probable operating conditions and alternatives.

Costs of overlay stock will vary with general lumber market conditions, and with the intracompany structure and affiliations. Assuming that the typical overlay operation will be a captive plant affiliated with a lumber-producing firm, lumber may be available at prevailing f.o.b. mill lumber prices. The ultimate cost of lumber for overlaying will depend on whether the overlay plant can obtain selected portions of each grade, or must purchase and use (by repairing or reselling) mill-run grade lumber. Long-term average f.o.b. mill values for mill-run grades of ponderosa pine lumber are shown in table 3,

Table 3.--Estimated costs of overlayable substrates of ponderosa pine lumber by three alternatives

Input by grade number	Thickness	Width	F.o.b. mill value[1]	Alternatives[2]		
				1	2	3
	Inches		Dollars/M b.m.	Dollars/M sq.ft.		
D Sel[3]	8/4	RW	229	229		
2C[3]	4/4	6	106	106		
2C	4/4	8	98	98		
3C	4/4	8	73	73	124	95
3C	4/4	12	84	84	151	104
4C	4/4	8	57	57	315	106
4C	4/4	12	63	63	390	108

[1]5-year averages (1966-70) for dry, finished lumber at inland mills.

[2]Alternative 1 assumes that only lumber meeting overlay substrate specifications is selected from each grade; 2 assumes that lumber is purchased by mill-run grade, with lumber not meeting substrate specifications being resold at next lower grade (for example, cull from 3C sold as 4C); 3 assumes that lumber is purchased by mill-run grade, with repairable lumber chemically repaired and nonrepairable lumber resold at next lower grade. See appendix I for calculations of substrate cost under alternatives 2 and 3.

[3]D Select and 2 & Btr. grades considered for specialty products only (stadium seating, fascia); most of lumber in the grade would be an acceptable substrate.

along with estimated costs of overlayable lumber substrate under each of three operating alternatives.

A series of pilot plant runs of 1 to 4 hours' duration were made to facilitate estimating direct material and labor costs per unit of production (table 4). During each run a single product involving one substrate size and one overlay was processed. Direct consumption or use of materials and labor was recorded and related to quantity of overlaid product manufactured. The pilot plant runs also provided a means of measuring such costs as machine setup time, cleanup time, and operational delays.

Indirect costs were estimated as accurately as possible for two levels of production—single laminator operated one shift per day, and single laminator operated two shifts per day. Operating assumptions and cost schedules used are discussed in the appendix.

Total projected costs of manufacturing overlaid lumber products, including substrate and direct and indirect processing costs, are aggregated in table 5. Some of the direct processing costs shown are likely to be higher than they would be in a fully developed production operation. Factors that tend to increase costs in the pilot plant include:

1. Relative inexperience of the operating crew. The crew is "borrowed" from other mill duties to work with the laminator at infrequent intervals, and may consequently be less efficient than a full-time production crew.
2. Lack of modifications and mechanical improvements that could be made on the roll laminator. Presumably, a production operation could capitalize on all the mechanical improvements made or underway to date, plus others that might become apparent in sustained production.
3. Lack of efficient equipment and facilities for lumber infeed, outfeed, and paper and adhesive loading. A production operation would benefit from more efficient auxiliary equipment and facilities.

Table 4.--Direct material and labor used, and costs incurred in pilot plant trial operations[1]

Overlaid lumber	Lumber substrate		Overlay		Adhesive		Operating labor and supervision		Setup-cleanup labor	
	Units used	Dollars	Units used	Dollars	Units used	Dollars	Units used	Dollars	Units used	Dollars
Cost basis	M sq.ft.	([2])	M sq.ft	21.60	Pounds	0.45	Minutes	0.272	Minutes	0.046
1- by 8-inch										
Per M lineal feet	0.71	([2])	0.91	19.66	14.1	6.35	14.6	3.97	3.2	0.15
Per M square feet	1.06	([2])	1.37	29.59	21.2	9.54	21.9	5.96	4.8	.22
1- by 12-inch										
Per M lineal feet (and M square feet)	1.06	([2])	1.28	27.65	16.2	7.29	12.9	3.51	3.2	.15

[1]Pilot plant trial runs to establish production costs were made with 1- by 8- and 1- by 12-inch 4/4 lumber substrates, overlaid with 5-mil vulcanized fiber, single-face overlay, with both edges wrapped.

[2]Substrate costs depend on input grade and available operating alternatives (see table 3). Substrate use reflects an average trim loss of 5.7 percent of the overlaid product.

Table 5.--Total projected production costs, in M square feet, for selected overlaid lumber products[1]

Production cost item	1- by 8-inch product, using--		1- by 12-inch product, using--	
	Grade 3 Common	Grade 4 Common	Grade 3 Common	Grade 4 Common
Substrate:[2]				
Alternative 1	$ 77.38	$ 60.42	$ 89.04	$ 66.78
Alternative 2	131.44	333.90	160.06	413.40
Alternative 3	100.70	112.36	110.24	114.48
Direct processing:				
Overlay	29.59	29.59	27.65	27.65
Adhesive	9.54	9.54	7.29	7.29
Labor	6.18	6.18	3.66	3.66
Electrical power	.41	.41	.27	.27
Indirect:				
Equipment investment and depreciation				
Single shift	2.30	2.30	1.53	1.53
Double shift	1.15	1.15	.77	.77
Building and facilities				
Single shift	.51	.51	.34	.34
Double shift	.25	.25	.17	.17
Taxes, insurance, maintenance (6 percent times investment)				
Single shift	.59	.59	.39	.39
Dougle shift	.30	.30	.20	.20
Total production:				
Substrate alternative 1				
Single shift	126.50	109.54	130.17	107.91
Double shift	124.80	107.84	129.05	106.79
Substrate alternative 2				
Single shift	180.56	383.02	201.19	454.53
Double shift	178.86	381.32	200.07	453.41
Substrate alternative 3				
Single shift	149.82	161.48	151.37	155.61
Double shift	148.12	159.78	150.25	154.49

[1]Cost calculations based on pilot plant test experience, plus operating assumptions and schedules included in the appendix.

[2]Refer to table 3 and substrate cost calculations included in appendix I. Indicated costs include 5.7 percent trim allowance.

PHASE II:
EVALUATION OF LUMBER REPAIR TECHNIQUES

The Need for Repair

Lumber overlays presently available cannot successfully span voids of any consequence, and generally do not adhere well over planer skip or rough grain. The necessary exclusion of lumber with such defects accounts for the low recovery of overlayable lumber from Common grades (see table 2). The low recovery is of primary concern, and indicates that suitable lumber repair methods must be developed before the overlay process can economically upgrade low-grade lumber. Phase II of this study was initiated to develope and evaluate the technical feasibility of a number of methods of repairing defects in lumber.

Lumber Defects and Potential Repair Techniques

Major defects that affect lumber substrate acceptability are unsound or chipped knots, knotholes, and rough or torn grain. Other less frequent defects include splits, wane, bark, rot or pitch pockets, crook, and pith streaks with associated juvenile wood.

The character of lumber defects varies with both lumber grade and width. The larger and more severe defects allowed in the lower grades and wider widths are more difficult to repair. Frequency of defect occurrence, however, is relatively independent of grade, and is generally lowest per square foot of board area in the wider widths. Average repairable defect occurrence and size in grades 3 and 4 Common lumber are illustrated in table 6. Histograms (figs. 5, 6) illustrate the frequency of distribution of the repairable defects by size classes. Grade 5 Common lumber has such extensive "nonrepairable" defect (see table 2) that it cannot be considered a potential source of overlay material.

For the defects being considered, the most promising methods of repair include wood plugs or patches, chemical foam repair, abrasive planing, and selective cut-up. Wood plugs or patches can be quickly applied with equipment commercially available. Chemical patches such as urethane foams can also be applied automatically, and can conform to virtually any size and shape of open defect. Abrasive planing can reduce or correct shallow open defect such as rough or torn grain. Selective cut-up procedures can be used to remove nonoverlayable defects from either repairable or cull lumber. All of these potential repair methods were evaluated during the second phase of the study.

Table 6.--Average width, length, area, and number of defects that require repair in repairable Common grades 3 and 4 lumber[1]

Lumber width and grade	Average defect size			Defects per square foot
	Width	Length	Area	
	Inches		Sq.in.	No.
4-inch:				
Grade 3	1.27	4.61	5.40	1.438
Grade 4	1.47	6.97	11.27	1.701
8-inch:				
Grade 3	1.89	5.06	10.42	1.381
Grade 4	2.46	8.53	24.91	1.249
12-inch:				
Grade 3	2.33	5.18	13.75	.827
Grade 4	2.60	12.03	27.01	.845

[1]Data based on repairable proportion of each grade, as shown in table 2.

Each of the repair methods evaluated was generally limited in application to the types of defects for which it appeared best suited. Defect types for which specific repair methods were tested are:

Repair method	Applicable defect types
Wood plugging	Unsound knots and knotholes less than 1½ inches in maximum diameter.
Chemical repair	Unsound, chipped or broken knots; knotholes; wane and other small voids; bark, pitch, or rot pockets.
Abrasive planing	Torn, chipped, or rough grain.
Selective cut-up	Full range of defects, including splits, severe checks, etc., that cannot be repaired by other methods.

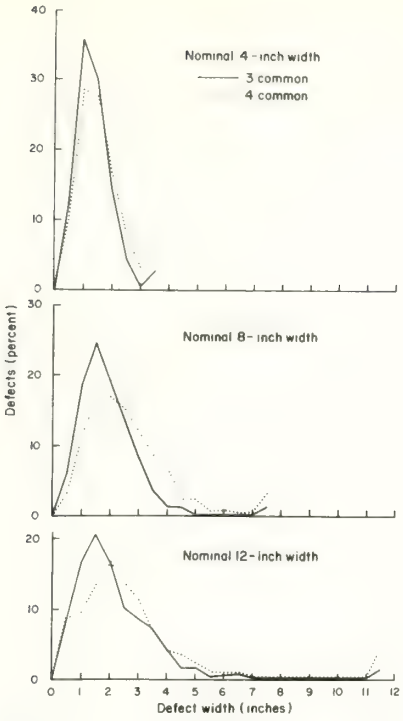


Figure 5.--Frequency of occurrence of defects, by defect width classes, in grades 3 and 4 Common ponderosa pine boards.

Pilot Tests of Repair Methods

Abrasive Planing

Abrasive planing tests were conducted with a double-belt combination sander-abrasive planer (fig. 7). Abrasive grits ranging from No. 24 to No. 100 were evaluated in various combinations on the double-belt unit at speeds up to 200 feet per minute. Accumulated data provided a basis for estimating abrasive planing capabilities in terms of feed rate, material removal, and surface characteristics for any belt combination.

An edge sander was added to the pilot production line to dress edge repairs and to provide for S4S abrasive finishing. Stock passed from the abrasive planer through the brush and vacuum lumber cleaning unit, and into the roll laminator.

Roll laminating requires a relatively smooth, unabraded surface; consequently, grits used are limited by the surface characteristics produced (fig. 8). Considering both production needs and surface acceptability, a combination of No. 36 grit (first belt) and No. 50 grit (second or smoothing belt) was found best for processing overlay stock.

Abrasive planing successfully "repairs" shallow defects such as planer skip, torn grain,

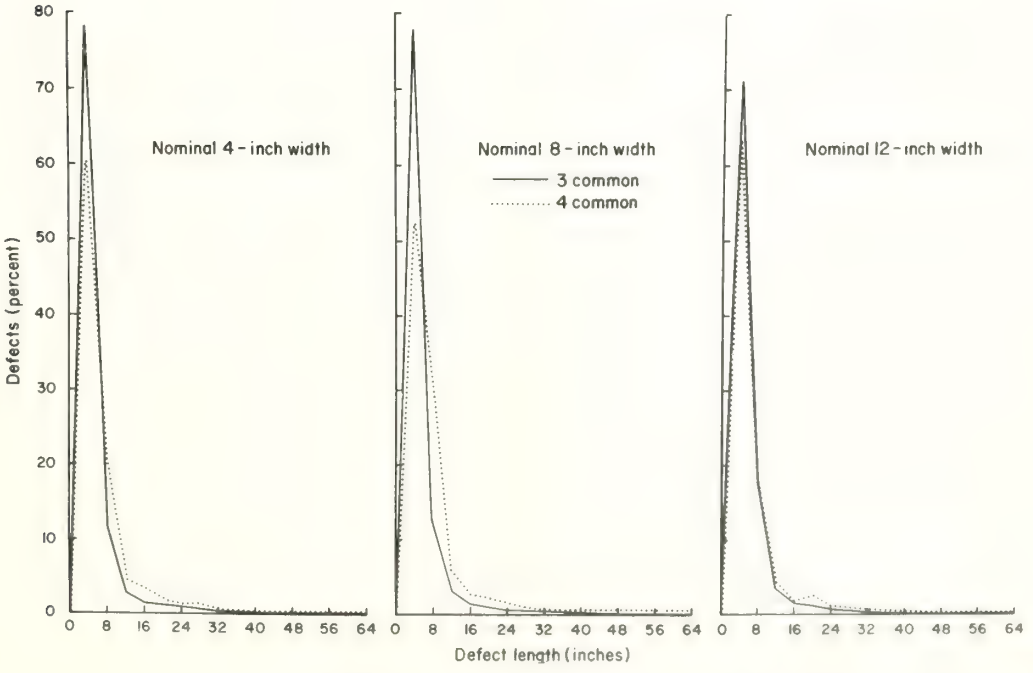


Figure 6.--Frequency of occurrence of defects, by defect length classes, in grades 3 and 4 Common ponderosa pine boards.

and the characteristic rough grain around knots (fig. 9). Abrasive planing also provides an ideal method of resurfacing patched lumber, because the wood or chemical patch must be machined down with minimal removal of stock from the board itself. The process also removes oxidized surfaces and pitch exudations, which improves the quality of the overlay glue bond. The slightly textured surface resulting from abrasive planing may also reduce the tendency of chemical patches to show through an overlay.

Ideally, rough lumber designated for overlaying would be abrasive planed, thus avoiding the rough and pulled grain defects caused by conventional knife planing. Abrasive planing is generally slower than conventional planing, however. A production alternative might be to surface material oversize with conventional planing, and complete surfacing to size with an abrasive planer.

The depth of defect that can be corrected by abrasive planing is limited by the specified minimal finished thickness of the stock. As a practical matter, abrasive planing is most effective in removing defects not exceeding 0.02 to 0.03 inch in depth (reducing 25/32-inch standard lumber to 3/4-inch). The removal of 0.02 inch of material from conventionally planed lumber successfully repaired all rough and pulled grain areas, and reduced thickness variation in the stock.

Figure 7.--The abrasive planer used in the study proved effective in repairing surface defects such as torn grain and planer skips.

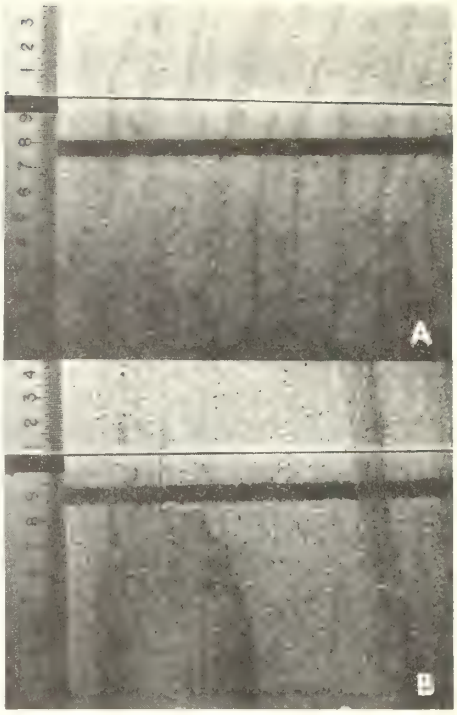


Figure 8.--Shadowlines magnify surface smoothness differences after sanding with No. 100 grit, A, and No. 50 grit, B, at a feed rate of 100 f.p.m.

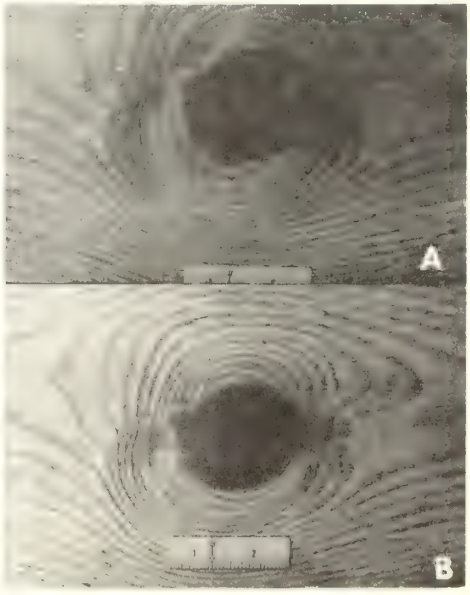


Figure 9.--Torn grain before, A, and after, B, a single pass through the abrasive planer, using No. 36 grit front sanding belt followed by No. 50 grit. Removal of 0.02 inch of material generally provided adequate repair.

Wood Plugging

Defects in lumber can be repaired by boring out the defect and inserting a wood plug, as in patching plywood panels. This method of patching was evaluated with a commercially available boring and plugging machine (fig. 10). The machine automatically bores out the defect (as positioned by the operator), sprays the hole with adhesive, cuts a wood plug, and positions it in the hole. A complete operating cycle requires 3 seconds. Boring depth and associated plug thickness can be varied, and multiple overlapping plugs can be inserted to replace larger defects.

A full range of patch thicknesses, including 5/32, 7/32, 3/8, and 25/32 inch, were tested. Plugs of 7/32-inch thickness proved to be the most convenient to install. Plugs the full thickness of the board are generally unsatisfactory because of a tendency of the boring bit to tear out the back perimeter of the hole. When plugs approaching half the board thickness (3/8 inch) are used, two-side patching can loosen or dislodge plugs set in the first side.

Wood plugging is a feasible means of repairing defects in lumber with relatively few, small defects (fig. 11). The wooden plugs are less noticeable on the board surface than synthetic patches, and have the same general texture as the board itself. Additional advantages are that plugging can be used for defects in the edge of the board (provided approximately two-thirds of the plug width is contained in the face of the board), and operation of plugging equipment requires little specialized training.

Wood plugging has the disadvantages of being relatively slow and expensive. Other disadvantages of plugging are restrictions in size and shape of defect that can be plugged, and slight separations that may develop around the plug. Any mismatch in grain direction and angle between board and plug results in slight separations around the patch, which contributes to showthrough and, under certain conditions, to overlay failure in the overlaid stock (fig. 12). Some tendency for the plug circumference to show through an overlay is apparent even in well-matched patches.

Although multiple plugs can be installed, experience indicates that they may not perform well. Each plug tends to force additional adhesive under the preceding plugs, raising them and creating a stairstep effect. For practical purposes, the size of defect that can effectively be plugged is limited by the size of the plug used. Equipment tested in the pilot plant used 1-9/16-inch plugs to repair defects up to approximately 1½-inch in diameter. This size plug will completely repair only about one-third of the boards in the 2 Common grade. Equipment is commercially available with 3-inch plugging

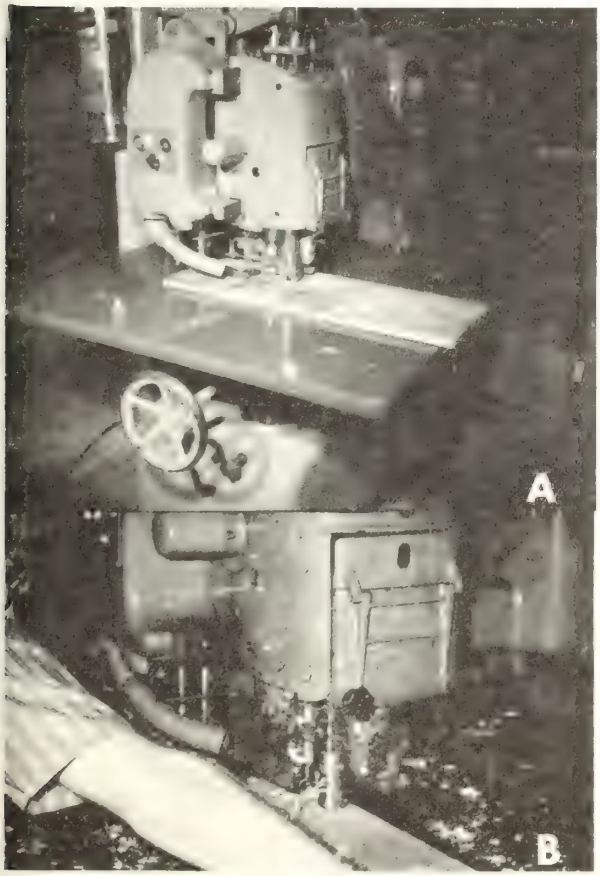


Figure 10.--Lumber plugging machine, A, bores out the defect, B, cuts a patch to size, applies adhesive, and sets the patch in a single sequenced operation.

Figure 11.--Wood plugs can be used to repair defects within the board, or on the edges of the board, provided approximately two-thirds of the plug is within the board.

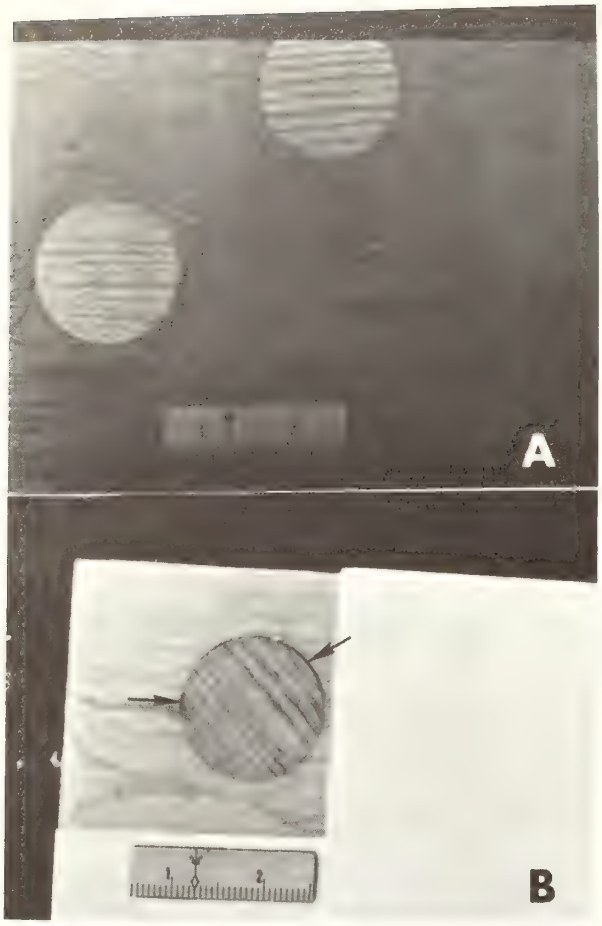


Figure 12.--Examples of matched and mismatched grain between plug and board. Well-matched grain, A, minimizes occurrence of gaps between plug and board, B, due to differential shrinkage.

capability, however, and with two heads accommodating two plug sizes. This larger equipment could repair practically all the defects in grade 2 Common lumber, creating a repaired, clear surface grade. The process is not a feasible repair method for grades 3 and 4 Common lumber, however, since too many of the defects exceed the capabilities of even the larger plugging equipment.

Costs of repairing lumber by plugging are high because of the relatively small amount of material that can be processed in a given period of time. One man operating one plugging unit can repair approximately 2,000 lineal feet (equivalent to 1,333 square feet) of 1- by 8-inch stock per 8-hour shift. Estimated costs of repairing such grade 2 Common lumber are itemized in table 7.

Table 7.--Estimated costs, per M square feet, of repairing grade 2 Common boards with wood plugs[1]

Cost item	Repair costs	
	Single shift	Double shift
Wood plug strips	$ 9.00	$ 9.00
Adhesive	1.00	1.00
Labor--		
semiskilled (1 man)	18.00	18.00
Equipment depreciation	14.52	7.26
Power, facilities, miscellaneous equipment, etc.	1.00	1.00
Refinish (planer)	4.50	4.50
Subtotal	48.02	40.76
Adjustment for material loss, contingency, etc. (costs times 0.11)	5.28	4.48
Total	$53.30	$45.24

[1]Pilot plant tests limited to 1- by 8-inch stock in which all defects could be repaired with 1-9/16-inch plugs. Operating assumptions and labor, equipment, and facility costs based on schedules included in the appendix.

Chemical Repair

Synthetic repair materials have been used to some extent to fill open defects in other wood products (plywood and so forth), and can be used in lumber. A primary requirement difference between synthetic repair materials for plywood and lumber is the need for lumber patching materials to "move" freely with dimensional changes in the board. Patching materials for overlay substrates must also provide a good surface for adhesion and create minimal show-through. They must also saw, machine, and nail in approximately the same manner as wood.

Early work with chemical repair techniques established that some routing or machining was necessary to "clean up" knotholes and other defects, and provide a firm surface for patch adhesion. Chemical patching (fig. 13) consequently involves a series of steps as follows:

1. Locating and identifying a patchable defect.
2. Routing or machining out the defect, leaving clean, solid wood at the perimeter.
3. Metering catalyzed repair chemical into the void.

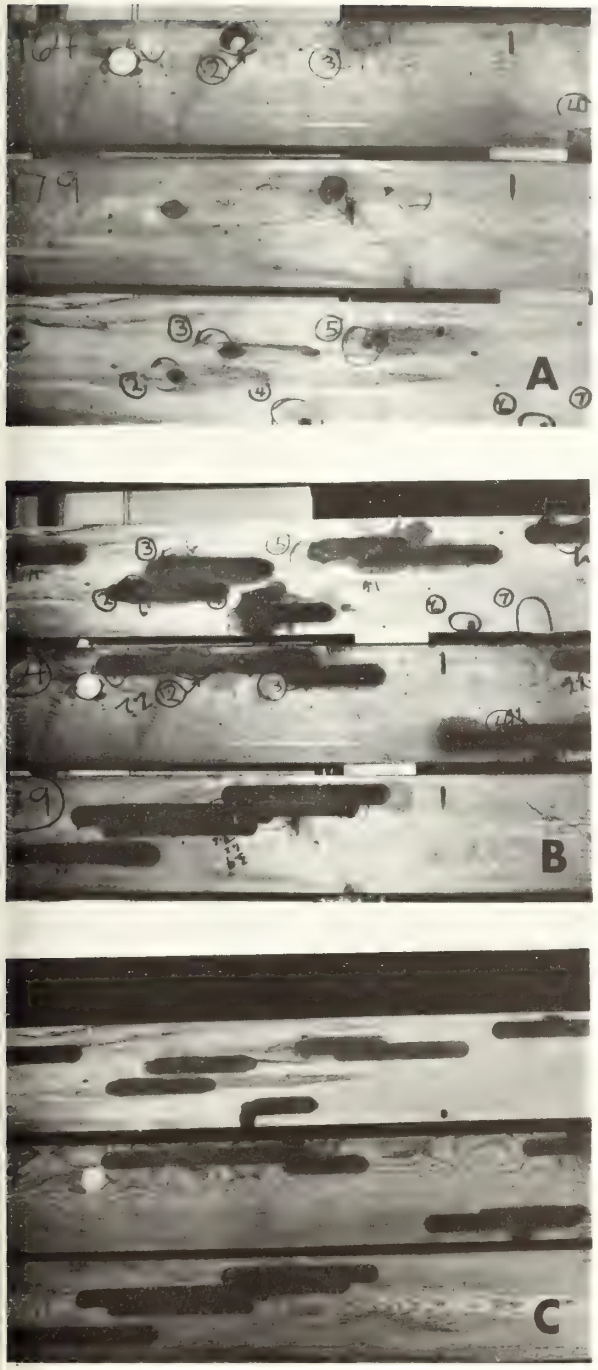


Figure 13.--A sequence of photos illustrates steps in the foam repair process: defects have been routed for repair, A; routed areas have been filled and allowed to set under pressure, B; repaired boards after a cleanup pass through the abrasive planer, C.

4. Applying a restraint against which the foam can expand, as a means of controlling density. (Most urethane foam systems have a free-rise foam density on the order of 2 to 10 pounds per cubic foot; consequently, restraint must be applied to achieve desirable patch densities of 18 to 20 pounds per cubic foot.)
5. Planing or sanding the repaired board to remove excess patch material and provide a smooth, uniform surface.

The urethane foams best satisfy all of the criteria for a chemical lumber repair material. They can be formulated to set in a matter of seconds, a necessity for production line processing.

A total of 18 urethane and similar resin systems were initially evaluated by the Forest Products Laboratory. Of four recommended for further evaluation in the pilot plant, two performed satisfactorily in the pilot trials.

Two significant variables in chemical repair were "packing" or patch density, and hole-edge geometry. Patch density can be varied by formulation, and by amount of resin loaded under restraint. Hole-edge geometry can be varied from a straight, vertical cut to a variety of tapered and shouldered cuts (fig. 14).

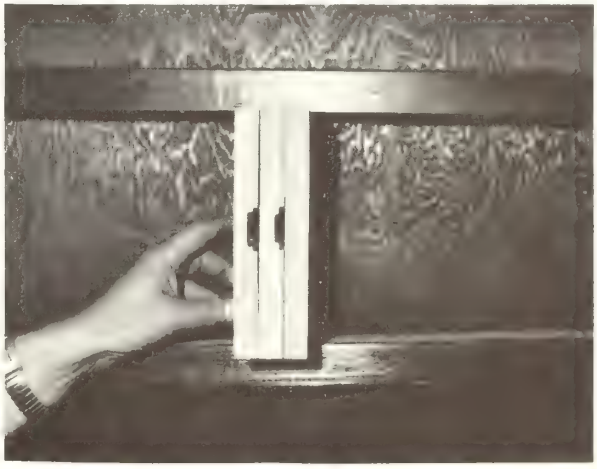


Figure 14.--Two variations of hole-edge geometry -- 1/8- and 1/4-inch shoulders -- were used in preparing defects for foam patch application. Test data indicated a slight advantage with the wider shoulder.

Extensive tests were conducted to evaluate two foam densities (18 to 20 and 28 to 30 pounds per cubic foot) and three hole-edge patterns (straight, 1/8-inch shoulder, and 1/4-inch shoulder). Evaluations indicated that both densities of foam performed very satisfactorily, with the lighter foam showing slight advantage.

Shouldered patches also performed better than straight patches, with test evidence slightly favoring the wider 1/4-inch shoulder. All final patching tests were made with the lighter foam density and both 1/4- and 1/8-inch shoulders. Very few patches failed and all failures were minute (fig. 15).

Commercial use of chemical patching methods would require a high degree of automation in locating, machining, and repairing defects. While the primary objective of the repair phase of the study was to establish a technically feasible method, methods of automatically locating and routing defects were also investigated. Scanners now in use for automatic veneer clipping were found to be generally satisfactory for lumber defect scanning, although the recognition pattern against which scanner information is checked would have to be modified to meet lumber repair requirements. Equipment suppliers have indicated that, with their present experience in plywood veneer scanning, automatic lumber scanning systems could easily be developed to control routing equipment as desired.

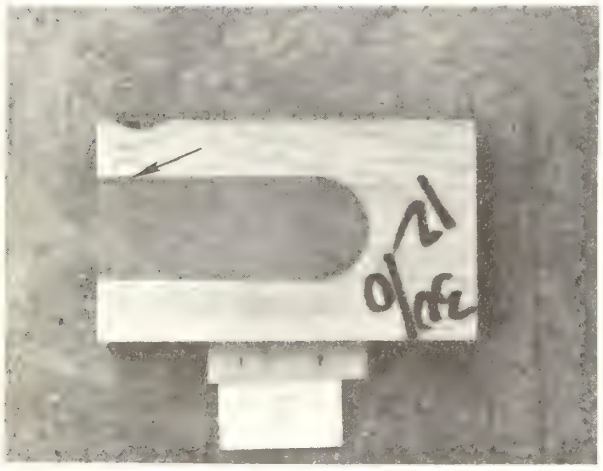


Figure 15.--The relatively obscure edge failure (arrow) which rejected this sample illustrates the rigid test requirements followed in evaluating potential repair materials.

An improvised optical scanning and routing system was devised with a single photocell and router (fig. 16). The router, a 2-3/4 horsepower, 23,000 r.p.m. unit, was mounted downstream from the scanner on a pneumatically actuated swinging arm. Signals generated by the scanning photocell activated the router to rout out defects. The rudimentary system operated successfully at feed rates of 90 to 100 feet per minute, routing up to 0.3 inch deep and 1¼ inches wide. A commercial operation would probably employ a bank of photocells, each scanning a proportion of the width of the board, and each controlling a downstream router. In this manner, defects located anywhere on the board and defects wider than a single router bit could be spotted and machined.

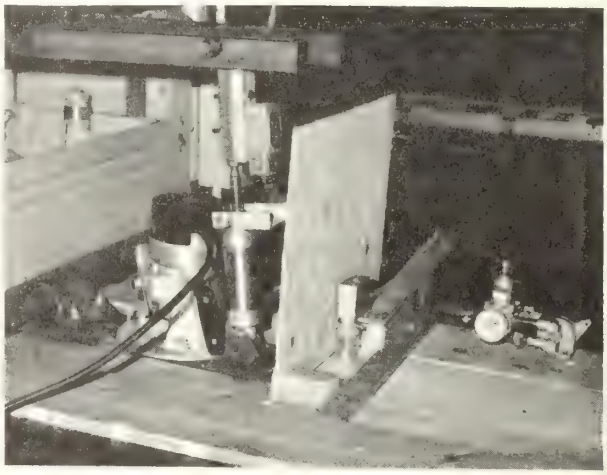


Figure 16.--A scanning photocell and router unit were used to locate and rout defects in the chemical repair study. The photocell, mounted ahead of the plywood baffle, activates an air cylinder which in turn raises and lowers the router at the proper time.

Most foam systems are fast-reacting two-component systems, in which the components must be precisely measured and mixed immediately before application. Foam patching consequently requires special equipment to meter the components, mix them, and dispense the catalyzed material. Pilot plant foam patches were made with a commercial urethane foam dispenser (fig. 17). The dispenser automatically meters and mixes the components, and provides for either manual or automatic dispensing of calibrated quantities or "shots" of the patching material. This type of air-operated high-speed mixer tends to introduce some air into the foam, however, causing nonuniform cell structure in the patches. Other commercially available mixing units may be more desirable for production use.

Chemical foam repair methods have the advantages of accommodating a wider range of size and type of defect than other methods, while providing a tight patch. Edge failure of the patches (fig. 15) is unusual, and generally indicates improper formulation, poor machining, or errors in patching technique. Durability and adhesion typically are excellent.

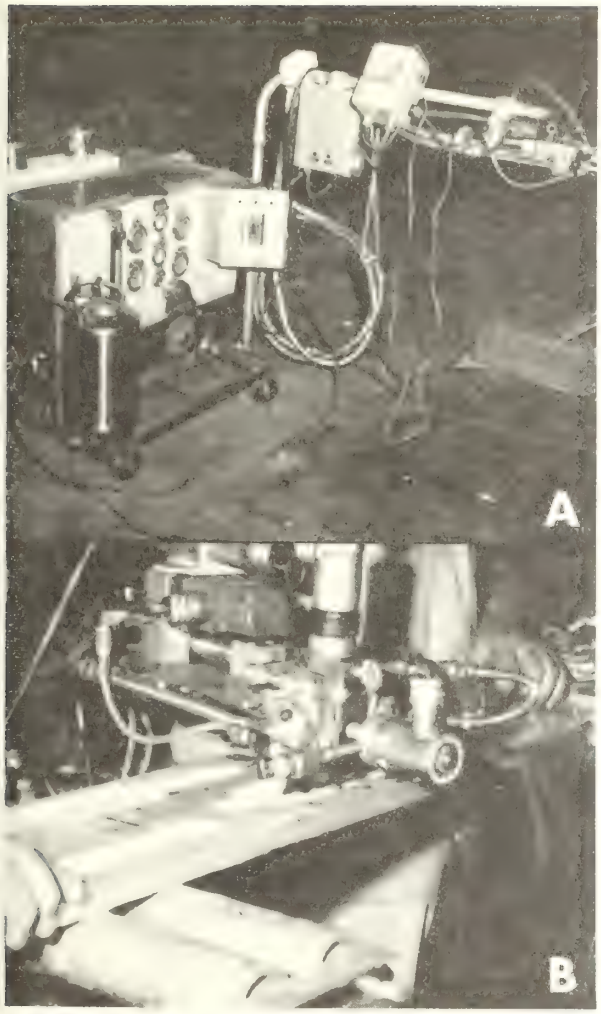


Figure 17.--Foam dispenser, A, and mixing and discharge assembly, B. The system automatically meters and mixes the components, and dispenses calibrated quantities of patching material.

Disadvantages of the method are that it requires a higher degree of quality control and technological sophistication than other methods, and requires considerably more specialized equipment. Because the foam patch material presently available is less hygroscopic than the surrounding wood, roll laminating overlays over the patches requires some adhesive and equipment modifications. Foam patches also tend to show through overlays because of differences between patch and wood texture. Showthrough resulting from foam patches, as well as knots and wood patches, can be minimized by abrasive planing, however.

The chemical repair work was carried out to evaluate the technical rather than economic feasibility of promising repair materials and methods. Costs that would be incurred in a commercial chemical repair operation can be estimated, however, by assuming use of an automated defect-locating and repair system based on equipment currently available commercially. Under such an assumption, estimated costs of chemically repairing grades 3 and 4 Common lumber are shown in table 8. Assumed production and cost schedules are included in the appendix.

Selective Cut-up

Low-grade lumber can also be repaired by ripping and crosscutting to remove unacceptable defects. Semiautomatic cut-up and end- and edge-gluing technology has been used for years in cut stock and lumber panel operations. Cuttings can thus be reassembled to produce an overlayable board or panel of practically any desired dimension. Overlaid panel products wider than conventional boards would have distinct marketing advantages. The width of overlay stock made up from cuttings would be limited only by the capacity of the roll laminator itself.

The feasibility of a low-grade lumber cut-up operation depends heavily upon the quantity and size of overlayable cuttings that are recoverable. To evaluate effects of board grade and width upon recovery, a method of reiterative simulated cut-up was developed. A sample of 600 boards was selected, representing widths of 4, 8, and 12 inches in grades 3 and 4 Common. The boards were examined, nonoverlayable defects located and outlined, and the boards photographed. Photos of the boards were projected at half-scale, and X and Y coordinates of all nonoverlayable defects measured and recorded in ¼-inch units. Board identification and defect coordinate data were transferred to punch cards for computer analysis.

A computer program[3] was written to calculate cutting recovery from individual sample boards, within constraints on cutting width combinations and cutting length. The program includes two basic routines, one to determine all possible permutations and combinations of specified sizes of cuttings for a board, and a

[3]*Erickson, Bernard J., and Donald C. Markstrom. Predicting softwood cutting yield with the computer. (Manuscript being prepared at Rocky Mountain Forest and Range Experiment Station.)*

Table 8.--Estimated costs,[1] per M square feet, of chemically patching repairable grades 3 and 4 Common boards, in 8- and 12-inch widths

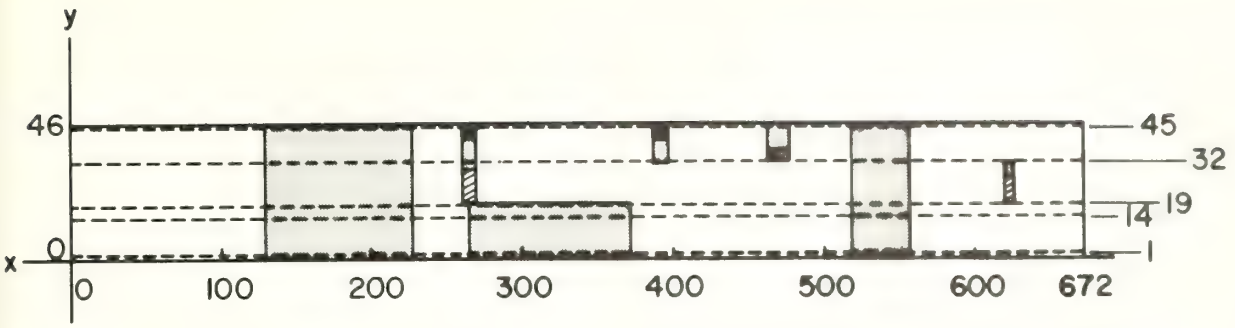
Cost item	1- by 8-inch product		1- by 12-inch product	
	Grade 3	Grade 4	Grade 3	Grade 4
Urethane foam	$14.50	$29.00	$11.60	$21.50
Labor:				
Supervisor (shared)	.70	.70	.70	.70
Skilled (1 man)	.91	.91	.91	.91
Unskilled (3 men)	1.65	1.65	1.65	1.65
Equipment depreciation:				
Single shift	3.78	3.78	3.78	3.78
Double shift	1.89	1.89	1.89	1.89
Electrical power	.27	.27	.27	.27
Building and facilities:				
Single shift	.68	.68	.68	.68
Dougle shift	.34	.34	.34	.34
Taxes, insurance, maintenance:				
Single shift	.96	.96	.96	.96
Double shift	.48	.48	.48	.48
Miscellaneous supplies, equipment:	1.00	1.00	1.00	1.00
Subtotal				
Single shift	24.45	38.95	21.55	31.45
Double shift	21.74	36.24	18.84	28.74
Adjustment for material loss, contingency, etc. (costs times 0.11)				
Single shift	2.69	4.28	2.37	3.46
Double shift	2.39	3.99	2.07	3.16
Total				
Single shift	27.14	43.23	23.92	34.91
Double shift	24.13	40.23	20.91	31.90

[1]Operating assumptions and labor, equipment, facility, and power costs based on schedules included in the appendix.

second to locate the cuttings on the individual board to maximize recovery (fig. 18). Program output indicates total loss area (including defects, saw kerfs, and edge trim) and total recovered area.

Table 9 describes maximum overlayable cutting recovery, and distribution by cutting widths, for lumber of grades 3 and 4 Common. As expected, the quantity of overlayable cuttings recoverable increases as the minimum allowable length of cutting is reduced, and as lumber grade increases. The lower recovery from nonrepairable boards (that is, those which were obviously too defective for conventional repair) is also to be expected. The lower recovery from the 8-inch boards resulted from an original program constraint that the number of saw kerfs on the board must equal the number of cutting widths. A subsample of 8-inch boards yielded approximately 8 percent more total recovery when the constraint was changed so that the number of saw kerfs on the board could be one less than the number of cuttings. The additional 8 percent recovery for the 8-inch boards makes the total recovery very comparable with the 4- and 12-inch boards.

A lumber defect scanning system such as that used in chemical repair trials could be



Board Grade: 4C
Width: 11-1/2 inches (46 units)
Length: 14 feet (672 units)
Coordinates: (0,0) (46,672)

Cutting Widths: 1, 2, and 3 inches
Length: 9 inches +

Optimum Cutting Widths and Sequence: 3, 1, 3, and 3 inches
Saw Kerf Coordinates: 1, 14, 19, 32, 45, and 46
Area Recovered: 19,404 sq. units
Area of Board: 30,912 sq. units
Percent Recovery: 62.77 percent

Defect Coordinates:
1. (0,127) (46,222)
2. (29,259) (38,265)
3. (0,262) (19,370)
4. (33,386) (41,396)
5. (35,463) (46,475)
6. (0,519) (46,556)
7. (27,620) (31,625)

Figure 18.--Diagrammatic sketch of a grade 4 Common 1- by 12-inch board, with associated program output data, illustrates the program developed for selective cut-up evaluation. Shaded areas represent defects that have been located by X-Y coordinates and blocked out. Lined areas represent additional material lost in cutting out defects.

combined with the optimizing computer program and an automatic-set ripsaw to automate the entire cut-up process. A fully automated cut-up system could substantially improve cutting quality and yield over that achieved by present methods, as well as increase potential production rates.

The optimizing cut-up program has considerable potential for application beyond the needs of the immediate study. The same basic techniques of automated defect scanning and computer evaluation of cutting alternatives can be extended to many other milling or cutting operations such as edging, trimming, molding, and cut stock production.

Overlaying On Repaired Lumber Substrates

Overlays may be applied to lumber repaired with wood plugs without any modification of materials or technique. Wood patches or plugs tend to show through 5-mil overlays, however, and the overlay may develop hairline failures around the edges of the plug. Both showthrough and overlay failure are minimized by matching texture and grain direction of board and plug.

Overlays applied to chemically repaired lumber with standard water-base adhesives may develop blisters over the patches, because excess moisture in the adhesive is not absorbed by the nonhygroscopic patch surface as it is by the wood. Use of a nonwater-base adhesive appears to be an easy solution, but it would require some modification of the laminator, depending on the specific type of adhesive selected. Another possible solution is to expand the overlay prior to application, by dampening or humidifying. The overlay would then be laminated in a fully expanded condition, however, and might fail in tension during any subsequent expansion of the substrate. A third solution would be to develop a more hygroscopic repair material, either by modifying the structure of the material or by adding hygroscopic fillers.

Table 9.--Maximum recovery of overlayable cuttings from mill-run and nonrepairable grades 3 and 4 Common lumber[1]

Lumber width and grade	Cutting constraints by minimum lengths and widths recovered														
	9-inch length					18-inch length					36-inch length				
	Inches wide			Total[2]	Basis: boards	Inches wide			Total[2]	Basis: boards	Inches wide			Total[2]	Basis: boards
	1	2	3			1	2	3			1	2	3		
	- - - Percent - - -				No.	- - - Percent - - -				No.	- - - Percent - - -				No.
MILL-RUN															
4 inches:															
Grade 3	24	50	1	75±0.7	100	22	46	2	70±0.9	100	17	38	1	56±1.4	100
Grade 4	21	43	1	65±1.6	100	18	38	1	57±1.7	100	14	26	1	41±2.0	100
8 inches:[3]															
Grade 3	31	28	8	67±0.7	100	27	25	10	62±1.1	100	22	18	8	48±1.7	100
Grade 4	25	22	9	56±1.8	100	22	21	6	49±1.8	100	14	15	5	34±1.7	100
12 inches:															
Grade 3	3	20	53	76±0.8	100	2	18	50	70±1.1	100	2	16	41	59±1.4	100
Grade 4	2	18	44	64±2.1	100	2	17	39	58±2.0	100	2	12	31	45±2.0	100
NONREPAIRABLE															
4 inches:															
Grade 3	22	49	0	71±2.0	16	19	44	0	63±2.9	16	14	35	0	49±3.6	16
Grade 4	20	40	2	62±1.8	54	16	35	2	53±1.9	54	12	21	2	35±2.2	54
8 inches:[3]															
Grade 3	24	27	5	56±3.2	17	22	18	9	49±3.6	17	14	13	7	34±4.3	17
Grade 4	18	18	8	44±4.1	27	16	17	5	38±3.8	27	11	13	4	28±3.6	27
12 inches:															
Grade 3	2	15	46	63±4.9	7	4	7	45	56±3.9	7	2	11	32	45±5.6	7
Grade 4	1	18	40	59±3.1	30	2	16	35	53±2.7	30	2	11	25	38±2.7	30

[1]Selected combinations analyzed were limited to combinations of 1-, 2-, and 3-inch cuttings, with the wider cuttings favored to the extent possible.
[2]Totals shown are class means ± one standard error.
[3]Recovery was about 8 percent higher with different program restraints; see text.

Performance Tests of Overlaid Lumber Products

Performance and durability of overlaid products manufactured by the roll lamination process are now being evaluated in exposure tests. The products being tested represent a range of Common lumber grade substrates, both repaired and unrepaired, and both prefinished and conventionally painted. Painted samples were finished with a titanium lead primer followed by two top coats of either acrylic latex or oil-base exterior white paint.

Product performance is being evaluated under a wide range of use conditions. Undesirable product performance may be characterized by actual delamination and physical degradation, or by objectionable visual features. Exposed products will be periodically examined to evaluate condition and performance of substrate (including repairs), overlay, adhesive bond, and finish. Figures 19 and 20 illustrate test installations established to observe the performance of overlaid siding under a variety of use conditions. Overlaid product samples are also exposed on test fences near Albuquerque, New Mexico, and Flagstaff, Arizona. Performance of test materials has been favorable to date.

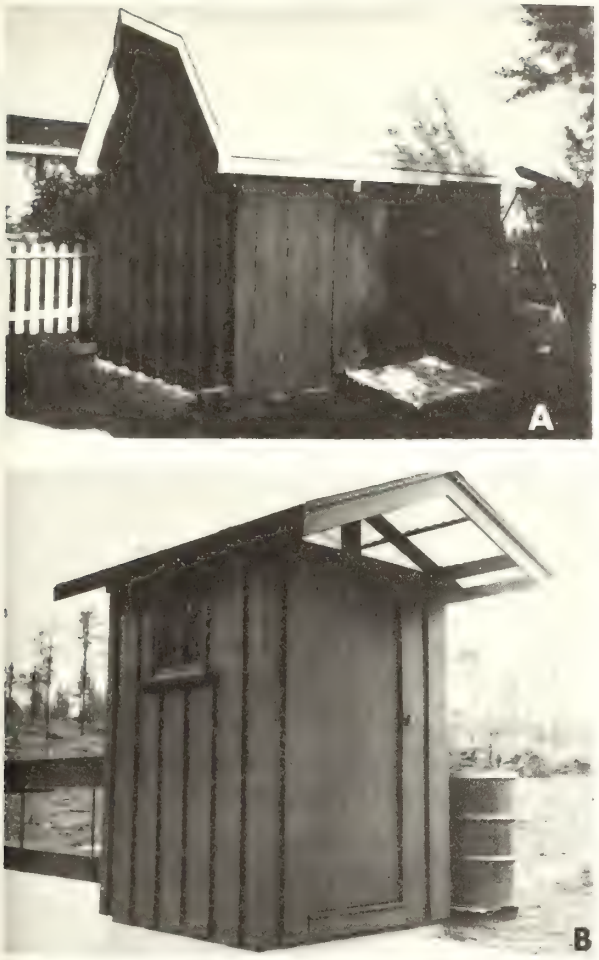


Figure 19.--Test installations of overlaid lumber siding produced in the study include a storage structure in Fort Collins, Colorado, A, and a gaging station on an experimental watershed near Flagstaff, Arizona, B. Test material, 5-mil vulcanized fiber on overlayable grades 3 and 4 Common ponderosa pine lumber, was installed in 1968.

Figure 20.--Other test installations of overlaid siding involved additional species and siding patterns: southern pine drop siding installed near Diboll, Texas, in 1964, A, and grade 2 Common western white pine bevel siding installed at Wilmington, Delaware, in 1968, B and C. Five-mil vulcanized fiber was used as the overlay on all test structures.

CONCLUSIONS

Technical Feasibility and Cost

1. The roll-laminating fiber overlay process is a technically feasible method of upgrading lumber that meets substrate requirements.

2. The low recovery of overlayable lumber from mill-run Common grades dictates that lumber defects must be repaired in the upgrading process to avoid excessive substrate costs.

3. Chemical repair methods are technically feasible and offer the greatest potential.

4. The wood plug repair method is also technically feasible, but is restricted in type and size of defect that can be repaired.

5. Abrasive planing successfully repairs or eliminates surface defects such as torn, pulled, or rough grain, minor skip, etc. It also improves the general surface characteristics of the lumber for subsequent overlaying.

6. Projected total costs of manufacturing overlaid lumber products, from either selected or chemically repaired substrate lumber, range from $107 to $161 per thousand square feet (table 10).

7. Commercial feasibility is currently restricted by the need for a better automated defect scanning and repair process. Adhesive systems better suited for overlaying on chemical foam patches are also needed.

Table 10.--Summary of projected production costs per M square feet for overlaid lumber products from selected or repaired substrates[1]

Cost item	1- by 8-inch product	1- by 12-inch product
Substrate	$60.00-112.00	$67.00-114.00
Overlay	29.59	27.65
Adhesive	9.54	7.29
Labor	6.18	3.66
Power	.41	.27
Indirect costs (Facilities, equipment, etc.)	1.70-3.40	1.13-2.26
Total product cost range	107.00-161.00	107.00-155.00

[1]Tables 3, 4, and 5 give detailed production costs by lumber substrate grade and use alternative.

Marketing Outlook

1. The basic concept of overlaid lumber products is generally acceptable to many potential users if the product affords distinct performance and/or price advantages.

2. Stronger market receptivity will depend upon future market development activities and improved manufacturing methods to reduce costs. Presently, the best prospects are for individual firms to develop smaller volume markets for specialty products.

3. Costs of production using repaired substrates, a necessity under most operating circumstances, restrict marketing possibilities to the higher value end products. Costs of overlaid products and currently used competitive products are compared in table 11.

Table 11.--Estimated production costs per M square feet of selected overlaid lumber products and f.o.b. mill prices of competitive wood products

Basic product	Overlaid product		Competitive commercial products	
	Description	Cost[1]	Description	Mill price[2]
Bevel siding, 10-inch	5-mil vulcanized fiber on repaired grade 3 Common, 1- by 10-inch[3]	$150	(1) Redwood,V.G.,3/4- by 10-inch (2) Cedar,Clear,3/4- by 10-inch (3) Hardboard lap, primed	$21 22 17
Board or standard pattern siding, 12-inch	5-mil vulcanized fiber on repaired grade 3 Common, 1- by 12-inch	151	Redwood,V.G., 1- by 12-inch	32
Fascia, 6-inch	5-mil vulcanized fiber on grade 2 Common, 1- by 6-inch	166	(1) Redwood,Clear, 1- by 6-inch (2) Pine,D Select, 1- by 6-inch	27 20
Stadium seating:	10-mil vulcanized fiber on 8/4 D Select:		Redwood Ht.,V.G.:	
6-inch	2- by 6-inch	307	2- by 6-inch	36
12-inch	2- by 12-inch	292	2- by 12-inch	39
Industrial shelving	5-mil vulcanized fiber or equivalent on repaired grades 3 and 4 Common, 1- by 12-inch	153	(1) Particleboard, 3/4-inch (2) Plywood, A-C, 3/4-inch	9 18

[1]Total estimated production cost, not including allowances for profit and risk.
[2]Industry average f.o.b. mill prices, 1971 (presumed to include allowances for profit and ris
[3]Overlaid bevel siding can also be produced by overlaying both sides of repaired 5/4 lumber a resawing, at a total estimated cost of $143/M square feet.

RECOMMENDATIONS

The study and conclusions reported here satisfy, and in some instances extend beyond, the objectives initially proposed for the pilot-plant investigation. The pilot operation has established the basic technical feasibility of the processes, but at the same time has indicated need for further development in several areas. Since overlaying and lumber repair, both separately and together, offer wide potential application, further development work is warranted. Recommendations include:

1. Develop an effective automated defect detection system to scan and control chemical repair of defective lumber.
2. Identify and test adhesive systems most suitable for overlaying chemical foam patches.
3. Evaluate the feasibility of using a foam adhesive to simultaneously make minor repairs and bond the overlay to the substrate.
4. Conduct further basic investigations of repair and overlay techniques in a facility where close control can be exercised over all aspects of substrate conditioning, in-plant operating conditions, and product testing.
5. Guide further work in repair and overlaying by the results of long-term tests of overlaid material now installed on test buildings and fences.
6. Evaluate in detail potential markets for specialty products for which repaired and/or overlaid lumber has unique advantages.

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APPENDICES

I. CALCULATED LUMBER SUBSTRATE COSTS

ASSUMPTIONS:

1. Lumber is available to the overlay operation at prevailing f.o.b. mill prices.
2. Lumber culled from each grade is resalable at f.o.b. mill price for next lower grade.
3. Under the repair alternative, lumber acceptable for repair is chemically repaired in a single-shift operation.

F.o.b. mill value, in M square feet, and substrate recovery, grades 3 and 4 Common ponderosa pine 4/4 lumber

Lumber width and grade	F.o.b. mill price	Substrate recovery		
		Acceptable	Repairable	Nonrepairable
		Percent		
8-inch:				
Grade 3	73	24	67	9
Grade 4	57	8	59	33
12-inch:				
Grade 3	84	24	67	9
Grade 4	63	8	59	33

Estimated cost of overlayable substrate from mill-run grades 3 and 4 lumber, by 8- and 12-inch widths

Cost item	1- by 8-inch product		1- by 12-inch product	
	Grade 3	Grade 4	Grade 3	Grade 4
Alternative 2 (without repair):				
Initial cost, M b.m.	$ 73.00	$ 57.00	$ 84.00	$ 63.00
Less resale value[1]	43.32	31.79	47.88	31.79
Net cost of overlayable lumber	29.68	25.21	36.12	31.21
Cost per board foot (or square foot)	0.1237	0.3151	0.1505	0.3901
Cost per M square feet	123.70	315.10	150.50	390.10
Alternative 3 (with chemical repair):				
Initial cost, M b.m.	73.00	57.00	84.00	63.00
Plus cost of repair[2]	18.09	25.37	16.08	20.65
Subtotal	91.09	82.37	100.08	83.65
Less resale value[3]	5.13	11.40	5.67	11.40
Net cost of overlayable lumber	85.96	70.97	94.41	72.25
Cost per board foot (or square foot)	0.0945	0.1059	0.1037	0.1078
Cost per M square feet	94.50	105.90	103.70	107.80

[1]Resale of 76 percent of 3C boards at 4C prices; 92 percent of 4C boards at 5C prices.

[2]Repair of 67 percent of 3C boards; 59 percent of 4C boards.

[3]Resale of 9 percent of 3C boards at 4C prices; 33 percent of 4C boards at 5C prices.

II. OVERLAY PLANT OPERATING CONDITION ASSUMPTIONS

Production costs depend in part on the production situation and the specific product. In calculating average production costs from pilot plant data, assumed operating conditions and product specifications must consequently be identified and described.

ASSUMPTIONS

1. Operating schedules.
   A. One shift per day (400 operating minutes), 5 days per week, 250 days per year.
   B. Two shifts per day (800 operating minutes), 5 days per week, 250 days per year.

2. Production levels.

	Capability of-- Single shift	Double shift
Lumber overlay:		
Lineal feet/day	40 M	80 M
Lineal feet/year	10MM	20MM
Lumber repair:		
Square feet/day	40 M	80 M
Square feet/year	10MM	20MM

3. Products (for cost analysis).

   4/4 nominal 1- by 8-inch and 4/4 nominal 1- by 12-inch } Overlaid one face and wrapped two edges

   All products trimmed to nearest 1-foot length.

4. Overlays.

   5-mil vulcanized fiber:

   10-inch width for 1- by 8-inch product.
   14-inch width for 1- by 12-inch product.

5. Adhesive.

   Cross-linking polyvinyl acetate.

6. Cost schedules.

   Equipment investment and depreciation, labor, facility, and power costs are calculated and prorated over assumed levels of production (see appendixes III, IV, V, and VI).

III. FACILITY COST SCHEDULE

Type of operation	Minimal space requirements	Monthly costs[1]	Chargeable costs for-- Single shift	Double shift
	Sq. ft.		(Per M lineal feet)	
Overlay	4,800	4,800x$0.06 = $288	$288/840M = $0.34	$288/1,680M = $0.17
			(Per M square feet)	
Repair (chemical)	9,600	9,600x$0.06 = $576	$576/840M = $0.68	$576/1,680M = $0.34

[1]Based on $0.06 square foot; includes utilities other than electrical.

IV. INVESTMENT AND DEPRECIATION SCHEDULE

Amortization period (N) = 5 years. Residual value (R) = 0

Equipment	Initial cost I	Average fixed investment ((I-R)(N+1)/2N)+R	Annual depreciation charge, straight li (I-R)/N
OVERLAY EQUIPMENT:			
Laminator and associated equipment	$50,000	$30,000	$10,000
Auxiliary plant equipment	15,000	9,000	3,000
Total	65,000	39,000	13,000
REPAIR EQUIPMENT:			
Chemical repair--			
Loader-unloader	10,000	6,000	2,000
Scanner	18,000	10,800	3,600
Router	15,000	9,000	3,000
Dispenser	10,000	6,000	2,000
Restraint unit	40,000	24,000	8,000
Abrasive planer	18,000	10,800	3,600
Transfer units (3)	12,000	7,200	2,400
Auxiliary equipment	37,000	22,200	7,400
Total	160,000	96,000	32,000
Wood plug repair--[1]			
Double-head plugger[2]	20,000	12,000	4,000

[1]Assumptions are that plugging operation can be accommodated by existing plant lumber handling and conveying equipment.

[2]Not suitable for repairing lumber lower than 2 Common in quality; therefore, of limited value to a repair-overlay operation.

CHARGEABLE INVESTMENT AND DEPRECIATION COSTS

Type of operation	Annual costs			Operation costs for--	
	Depreci-ation	Interest[1]	Total	Single shift	Double shift
				(Per M lineal feet)	
Overlay	$13,000	$2,340	$15,340	$15,340/10,000M = $1.53	$15,340/20,000M = $0.7
Repair:				(Per M square feet)	
Chemical	32,000	5,760	37,760	$37,760/10,000M = $3.78	$37,760/20,000M = $1.8
Wood plug[2]	4,000	720	4,720	$4,720/325M = $14.52	$4,720/650M = $7.2

[1]Based on average fixed investment at 6 percent.

[2]Based on estimated repair capacity of 2,000 lineal feet of 1- by 8-inch stock per shift, or 325,000 square feet per year per plugging machine.

V. LABOR COST SCHEDULE

Position	Hourly rate[1]	Labor used per operating shift, and cost					
		Overlay[2]		Repair			
				Chemical		Wood plug	
		No.	Cost	No.	Cost	No.	Cost
Supervisor (lamination and repair)	$7.00	½	$3.50	½	$3.50	--	--
Skilled labor (laminator operator, repair crew foreman)	4.56	1	4.56	1	4.56	--	--
Semiskilled labor (patcher operator)	3.00	--	--	--	--	1	$3.00
Unskilled labor (overlay, repair crews)	2.75	3	8.25	3	8.25	--	--
Total	--	4½	16.31	4½	16.31	1	3.00

[1]Includes 20 percent addition to basic wage rate, for administrative overhead costs and fringe-benefit programs.

[2]In addition, setup and cleanup will require one crew member, working one man-hour overtime before and after each single- or double-shift operating period.

VI. ELECTRICAL POWER COST SCHEDULE

(Estimated use and cost same for overlay and chemical repair operations)

Power use and costs	General	Single shift	Double shift
POWER USE:			
Calculated peak plant load	= 98 M watts		
	= 98 KVA		
Assuming .80 power factor, true power use	= 78.4 KW		
Assuming peak power use, monthly use		78.4x168 = 13,171 KWH	78.4x336 = 26,342 KWH
POWER COSTS:			
Assuming laminator operation is added to an existing manufacturing facility, the cost of electrical power would be an 'add-on' cost at lowest commercial rate:			
Demand charge		78.4x$1.25 = $98.00	156.8x$1.25 = $196.00
Energy charge		13,171x$0.01 = $131.71	26,342x$0.01 = $263.42
Total costs			
Monthly		$229.71	$459.42
Per M lineal feet[1]		$229.71/840M = $0.27	$459.42/1,680M = $0.27

[1]Per M square feet for chemical repair operation.

VII. SUMMARY -- UNIT COSTS APPLICABLE TO LUMBER REPAIR AND OVERLAY

Type of operation and cost item	Substrate item (4/4)			Cost per unit	Cost per unit for--	
	Select	Mill-run	Repaired		Single shift	Double shift
	Dollars/M square feet					
OVERLAY:						
1- by 8-inch product						
Grade 3 Common	$73	$124	$ 95			
Grade 4 Common	57	315	106			
1- by 12-inch product						
Grade 3 Common	84	151	104			
Grade 4 Common	63	390	108			
Overlay (5-mil vulcanized fiber)				$21.60/M sq. ft.		
Adhesive				0.45/pound		
Labor, operating				0.272/minute		
Labor, setup and cleanup				0.046/minute		
Electrical power				0.27/M lineal feet		
					(Per M lineal feet)	
Equipment investment and depreciation					$1.53	$0.77
Building and facilities					.34	.17
Taxes, insurance, maintenance (at 6 percent)					.39	.20
CHEMICAL REPAIR:						
Urethane foam				$0.001/sq. inch of defect		
Labor				3.26/M sq. ft.		
Electrical power				0.27/M sq. ft.		
Miscellaneous supplies				1.00/M sq. ft.		
					(Per M square feet)	
Equipment investment and depreciation					$3.78	$1.89
Building and facilities					.68	.34
Taxes, insurance, maintenance (at 6 percent)					.96	.48

Mueller, Lincoln A., Roland L. Barger, Arthur Bourke, and Donald C. Markstrom.
1972. Roll laminating fiber overlays on low-grade ponderosa pine lumber. USDA For. Serv. Res. Pap. RM-97, 28 p. Rocky Mt. For. and Range Exp. Stn., Fort Collins, Colo. 80521.

Pilot plant tests were conducted with recently developed roll laminating equipment and thermosetting emulsion adhesives. Lumber that met substrate quality requirements was satisfactorily overlaid at speeds up to 180 feet per minute. Costs of overlaying, exclusive of substrate, ranged from $0.04 to $0.05 per square foot of product. A high proportion of Common grade lumber contains defects that cannot be overlaid. A second study phase found that abrasive planing (for surface defects) and urethane foam fillers (for voids) are promising repair techniques. Using selected or repaired lumber, overlaid products can be manufactured within a competitive price range. There is no strong market acceptance for such products at present, however, and aggressive market development will be needed. Commercial feasibility is currently restricted by the need for an effective automated defect repair system, and by lack of assured markets.

Keywords: *Pinus ponderosa*, forest products, lumber finishing.

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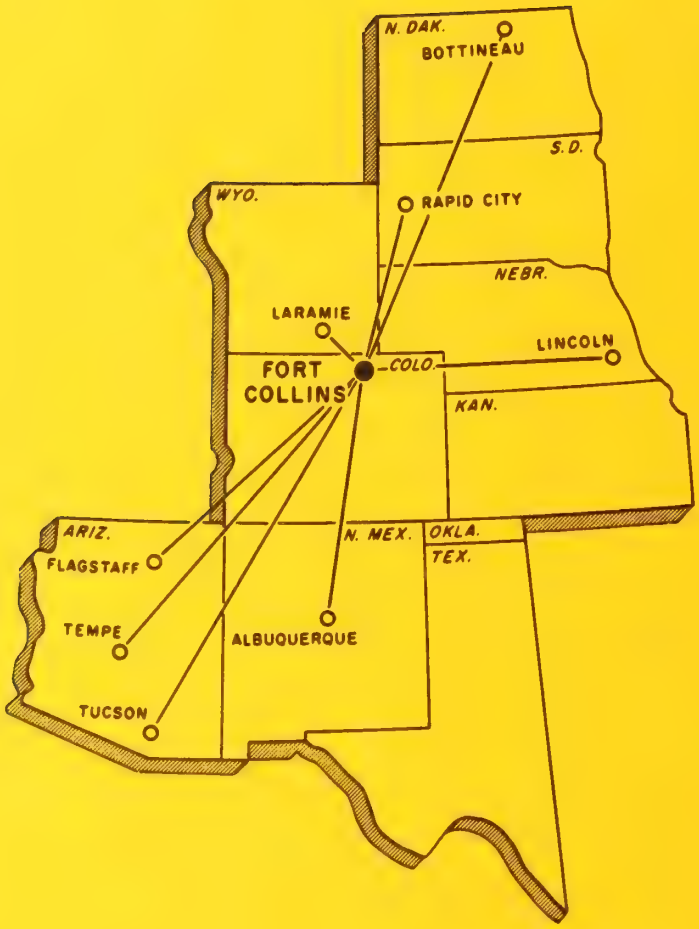
Mueller, Lincoln A., Roland L. Barger, Arthur Bourke, and Donald C. Markstrom.
1972. Roll laminating fiber overlays on low grade ponderosa pine lumber. USDA For. Serv. Res. Pap. RM 97, 28 p. Rocky Mt. For. and Range Exp. Stn., Fort Collins, Colo. 80521.

Pilot plant tests were conducted with recently developed roll laminating equipment and thermosetting emulsion adhesives. Lumber that met substrate quality requirements was satisfactorily overlaid at speeds up to 180 feet per minute. Costs of overlaying, exclusive of substrate, ranged from $0.04 to $0.05 per square foot of product. A high proportion of Common grade lumber contains defects that cannot be overlaid. A second study phase found that abrasive planing (for surface defects) and urethane foam fillers (for voids) are promising repair techniques. Using selected or repaired lumber, overlaid products can be manufactured within a competitive price range. There is no strong market acceptance for such products at present, however, and aggressive market development will be needed. Commercial feasibility is currently restricted by the need for an effective automated defect repair system, and by lack of assured markets.

Keywords: *Pinus ponderosa*, forest products, lumber finishing.


N. DAK.
BOTTINEAU
S. D.
WYO.
RAPID CITY
NEBR.
LARAMIE
LINCOLN
FORT COLLINS
COLO.
KAN.
ARIZ.
N. MEX.
OKLA.
TEX.
FLAGSTAFF
TEMPE
ALBUQUERQUE
TUCSON

PREDICTING SOFTWOOD CUTTING YIELDS BY COMPUTER

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Bernard J. Erickson and Donald C. Markstrom

Program CUTUP in Brief

Currently, major emphasis in improving wood conversion efficiency is concentrated in three areas: (1) improving yields from the resource, (2) reducing waste and residues, and (3) reducing processing errors resulting from repetitive human decisions. The program described here can contribute to greater efficiency in all of these areas. Automated defect-sensing methods now being developed offer the possibility of feeding continuous defect data to a computer as input to the type of optimizing program described, thereby automating the whole cut-up decision process.

A computer program CUTUP to predict the maximum yield of cuttings obtainable from softwood lumber is described in this paper. The program calculates cutting recovery (given cutting width and length constraints and defect location on the board), and will predict the maximum yield of cuttings of a specified grade, for a softwood cut-up and edge- and end-gluing operation.

The conventional practice in softwood cut-up operations is to first rip the board into prescribed cutting widths in a manner to maximize recovery, and then crosscut the full-board-length cuttings to remove defects. The CUTUP computer program simulates this practice systematically, (1) locating full-board-length cuttings of specified widths and sequence to maximize recovery, (2) crosscutting to remove defects, and (3) measuring the areas of all cuttings of a specified length or longer. The recovered area excludes (1) the area of defects, (2) areas between defects, or between a defect and the end of the board, where the recoverable length is less than the specified minimum, and (3) areas of all saw kerfs. The maximum number of rips is also specified in the program.

This program differs fundamentally from computer programs developed to predict yield of cuttings from hardwood cut-stock operations, where the usual sawing practice is to alternately crosscut and rip.[2] [3] Hardwood programs systematically scan the board to locate and measure cuttings of prescribed width and length between defect areas, with the largest specified cutting considered first. The cuttings can then be removed from the board by starting with either a crosscut or rip, and alternating back and forth, taking as many cuts as possible during each operation. Softwood and hardwood programs are similar, however, in that the same format is used to record board and defect data on the input cards.

[2] *Englerth, G. H., and D.E. Dunmire. Programing for lumber yield. For. Prod. J. 16(9): 67-69. 1966.*

[3] *Wodzinski, Claudia, and Eldona Hahm. A computer program to determine yields of lumber. U.S. Dep. Agric., For. Prod. Lab., 33 p. Madison, Wis. 1966.*

Characterizing Boards and Defects

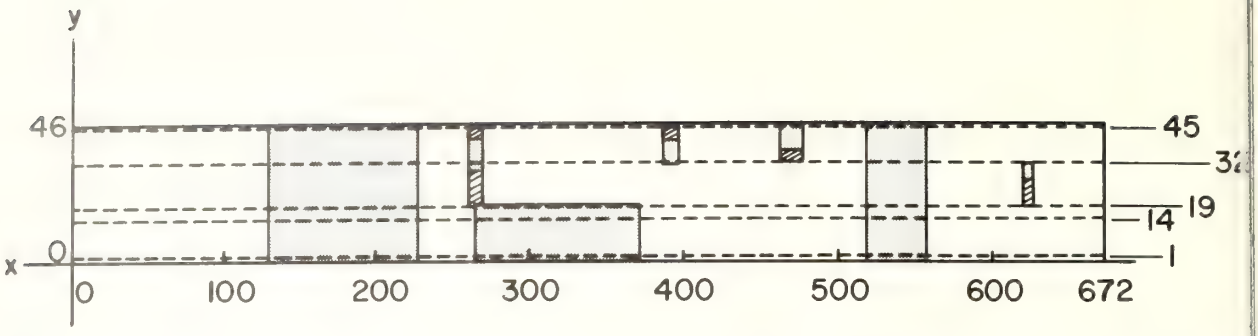
Each board is considered to have X and Y axes, with its lower left corner at (0,0), its length along the X axis, and its width along the Y axis. The board size is described and defects are located by 1/4-inch coordinates, which designate the lower left and upper right corners of the areas (fig. 1). All measurements are expressed in 1/4-inch units, which can be used directly in calculating recovery of cut-up stock.

Data cards describing the boards and defects are punched in the following manner: The first card lists the board grade code in columns 6 and 7, the board number in columns 32 through 36, and total number of defects in columns 69 through 72. The second card gives the coordinates of the board, and each of the remaining cards gives the coordinates of a single defect. The lower left Y coordinates of the board and the defects are punched in columns 1 through 3 and the X coordinates in columns 5 through 7. The upper right Y coordinates are punched in columns 13 through 15 and the X coordinates in columns 17 through 19. The sequence of the defect cards in the deck must be the same as that of the defects, from left to right across the X axis of the board.

The total number of cards for each board equals the number of defects plus two.

The program was run with a sample of 600 boards selected from surfaced yard lumber at the Duke City Lumber Company. One hundred boards were randomly selected in each of six categories: grades 3 Common and 4 Common, in nominal widths of 4, 8, and 12 inches.

The boards were examined and defects outlined. As a convenience, the boards were then photographed with color transparency film. The slides were projected at one-half scale on rear-projection translucent glass to facilitate measuring board and defect data.



Board grade: 4C
width: 11½ inches (46 units)
length: 14 feet (672 units)
coordinates: (0,0) (46,672)

Cutting widths: 1, 2, and 3 inches
length: 9 inches +

Optimum cutting widths and sequence: 3, 1, 3, and 3 inches
Saw kerf coordinates: 1, 14, 19, 32, 45, and 46
Area recovered: 19,404 sq. units
Area of board: 30,912 sq. units
Percent recovery: 62.77 percent

Defect coordinates: 1. (0,127) (46,22
2. (29,259) (38,2
3. (0,262) (19,37
4. (33,386) (41,3
5. (35,463) (46,4
6. (0,519) (46,55
7. (27,620) (31,6

Figure 1.--Diagrammatic sketch of a grade 4 Common 1- by 12-inch board, with associated program output data, illustrates the program developed for selective cut-up evaluation. Shaded areas represent defects that have been located by X-Y coordinates and blocked out. Lined areas represent additional material lost in cutting out defects.

Using the Program

Boards of different species, sizes, and grades could be sampled and the program used to evaluate the following:

1. Area recovered using alternative rip combinations.
2. Efficiency (in percent recovery) obtained from alternative widths of boards, for specified rip widths.
3. Effects of grade on rip recovery, for given species and specified rip widths.
4. Effects of adding or deleting rip widths from the array now used.
5. Alternative costs of input stock of various species, grades, and widths, based on predicted potential.

The program can undoubtedly be used to evaluate many other situations.

Program CUTUP

Program CUTUP is a set of three main programs — PERMU, CONST, and RECVRY. Program PERMU prepares a table of all possible cutting combinations for the N cutting widths (with M saw blades) to be considered for a given board-width class. User-selected cutting combinations are input to program RECVRY, which fits the cuts to individual boards to obtain maximum recovery area. Program CONST has one subroutine, XOUT, which outlines or "x's out" the defective areas of a board by r lating defect, X, Y coordinates to computer co storage locations. The program prepares an i put file of nonrecoverable board-defect area by specified cutting widths, for use in th RECVRY program. For boards 7.5 inches a wider, CONST requires considerable comput time. If narrower widths are to be processe programs CONST and RECVRY may be ru together as one program, with the output fro CONST used directly as input to RECVRY. Th eliminates the necessity of saving CONST ou put (Tape) for further processing by progra RECVRY.

The board-defect data cards which are inp to program CONST should be edited and err checked before use. If a large amount of data to be processed, the data should be tape file for ease of handling. A sample edit and card-t tape program is included with the program lis ings in appendix 2.

The basic content and purpose of each pr gram and subroutine is described in the sectio that follow. The order and format of input co trol cards for each program are also specifie Variable names are defined in the source listin for each program. A sample output of an app cation of program CUTUP is shown in appendi 1, which also further explains the overall pr gram operation.

Program PERMU, CONST, and RECVR were originally written in the BASIC progran ing language for use on a time-sharing compute

system. The programs were modified, expanded, and rewritten in FORTRAN extended for use on a Control Data Corp. 6400 computer,[4] and have been tested on the CDC 6400 computer system at the Colorado State University Computing Center.

Program PERMU

This program produces a table of possible cutting combinations for a specified board width, cutting or ripping widths, and cutting positions (kerfs). The computational procedure is based upon the principle that if one event A can take place in m ways, and a second event B can take place in n independent ways, then the number of ways in which both events can take place is mn. This principle can be extended to any number of independent events. The procedure was applied to the problem of cutting boards into different widths where each saw kerf is an event which can happen in m positions of the saw blade over a board. By expanding this technique, all combinations previously derived for narrower cutting widths and fewer cutting blades are saved for possible application in dealing with wider cutting widths and more cutting blades.

The procedure was used to process data involving three cutting widths of four, eight, and twelve 1/4-inch units (Q.I.U.), and five kerfs or cutting positions. Sample board widths ranged from 14 to 46 Q.I.U. To accommodate additional cutting widths and/or cutting positions, test parameters and array dimensions would need to be changed, as specified by the analysis problem.

Program Control Card Type 1. FORMAT (315)

Column		
1-5	IBWDT	Overall board width in 1/4-inch units (Q.I.U.)
6-10	NSIZE	Number of different cutting sizes or rip widths to consider, MAX = 5.
11-15	NSWBL	Number of machine saw blades available, MAX = 6.

Program Control Card Type 2. FORMAT (515)

Column		
1- 5	KUT(1)	Size of cutting width 1, in Q.I.U.
6-10	KUT(2)	Size of cutting width 2, in Q.I.U.
11-15	KUT(3)	Size of cutting width 3, in Q.I.U.
16-20	KUT(4)	Size of cutting width 4, in Q.I.U.
21-25	KUT(5)	Size of cutting width 5, in Q.I.U.

Program CONST

This program constructs, in computer core storage, a board of variable width and length dimensions, and positions the location of defects in the board according to their coordinates. Board and defect coordinates are expressed in Q.I.U. to the X, Y coordinate system.

The amount of core storage available in the computer determines the size of boards which can be analyzed by this program. The array LWB(I,J), **L**ength and **W**idth of **B**oard, is dimensioned according to the length (J) and width (I) of the largest boards to be analyzed in Q.I.U. If the largest boards to be processed are 11.5 inches by 16 feet, the array LWB(I,J) would be dimensioned I =46, J = 768, resulting in 35,328 computer core locations to store all possible locations of defects.

Input data are contained in the set of cards which specify the board and defect coordinate values for one board (described in Characterizing Boards and Defects). The defects are positioned in LWB according to increasing defect coordinates in the J, or length, dimension of LWB(I,J).

If a large amount of data is to be processed, and is arranged or sorted by some criteria such as increasing board numbers within a board-width class, an option is provided to analyze a selected sub-set from the complete file. This option is exercised by two control parameters labeled NBSTR and NBEND, where NBSTR is the number of the first board in the sub-set and NBEND is the number of the last board in the sub-set to be processed.

A user input parameter labeled LBTD is a test variable used for setting a minimum acceptable length between defects. If an area between two defects (or between a defect and the end or start of a board) is less than LBTD (in Q.I.U.), the area is blocked out and treated as a defect area in the final scan of the board to locate all defect areas.

For each input board, program CONST operates in the following manner:

1. The board ID or Header Card is read, setting the variables NGRD, (board grade class), NBRD (board number), and NDEF (number of defects in board).
2. A board coordinate card is read **defining** the X-dimension (Width) as the ordinate and the Y-dimension (Length) the abscissa of the board to be processed. This notation is

[4] *The use of trade and company names is for the benefit of the reader; such use does not constitute an official endorsement or approval of any service or product by the U. S. Department of Agriculture to the exclusion of others that may be suitable.*

reversed from the normal X, Y notation because of computer core storage procedure.

3. A set of defect coordinate cards is read until an END-OF-BOARD data card is encountered (IDXS=999).

The coordinates for each defect are positioned in an array by a pointer according to their order of occurrence within the board. Using the minimum length between defects test (LBTD), the defect array is scanned to find areas between defects which are less than LBTD. Defect location variables NX, LDS, and LDE are determined and passed to subroutine XOUT, along with the board array LWB, by the use of a COMMON statement. Subroutine XOUT then blocks out or "x's-out" the defined area of the defect in the board. This process continues until all defect areas have been positioned in the LWB array.

Indexes are now determined for a scan of the board to accumulate total defect area for NSIZE desired cuttings over a range of possible starting cut positions determined by board width. The total defect area for the board is written to an output file (Disk or Tape) for input to program RECVRY. The next board ID or Header Card is read and the process is repeated until an end-of-file is encountered in the board input data.

Program Control Card. FORMAT (315)

Column		
1- 5	LBTD	Minimum length between defects limitation (Q.I.U.)
6-10	NBSTR	Board number to start analysis
11-15	NBEND	Board number to end analysis

Board Defect Data Card Deck

NDEF + two cards for each board to be processed plus an END-OF-BOARD Card.

Program RECVRY

This program computes the nondefective areas in a board, and simulates a number of possible cuttings, limited by the width of the board and the combinations of cutting sizes desired, to determine the best combination to use for maximum recovery.

Input for the program is the board-defect area file (Tape or Disk) from program CONST, and a user-selected set of cutting combinations generated by program PERMU to be evaluated. The cutting combinations are input to the program in a DATA statement, array KPCT. The coding order is explained in the program listing.

The program reads a title card and an input parameter control card. The parameter LPRM is the lower limit of combined cuttings to b evaluated from the combination sets in arra KPCT. Only combined cuttings greater tha LPRM are used to evaluate the best fit, thu eliminating cutting combinations which do n use the entire width of the board. The variab NSIZE and the array KUT are set from valu coded in DATA KSZE.

The board ID and board coordinates ar read from the input file, along with board d fect areas. Areas of nondefect are compute from defect area and area of the board, an saved. Indexes are set for selecting cutting cor binations from array KPCT to obtain maximun recovery for the board. The number of sa kerfs which can be placed within the bounds o the board is determined. A saw kerf may b adjacent to the lower or upper edges of board, or it may lie within the board itsel There is no provision in this program fo straightening the edges and ends of the boar to assure a straight board. A warped board ma be utilized, however, by crosscutting into short lengths or ripping into narrow widths, b assigning appropriate defect coordinates. Th sum of the cutting widths and saw kerfs canno exceed the board width plus one unit.

A total recovery area is computed from th nondefective area data for a selected combin tion of cuttings. This value is stored as th "best" until a larger recovery area is obtaine from a different combination of cuts, which the replaces it as the "best." After all acceptab combinations have been evaluated for best fi the individual board recovery summary printed out. Totals are accumulated for tot recovery output by board grade and size cla until an end-of-file is encountered in the inpu data file.

Program Control Card Type 1. FORMAT (4A10)

Column		
1-40	TITLE	Short title to identify data bei processed.

Program Control Card Type 2. FORMAT (415)

Column		
1- 5	LBTD	Minimum length between defec control: same value as in CONS
6-10	LPRM	Lower limit of combined cuttin control: used to select combinatio of cutting sizes.
11-15	NBSTR	Board number to start analysis f recoverable area.
16-20	NBEND	Board number to end analysis f recoverable area.

Board numbers (NBRD) to be included in the analys should be ≥NBSTR and ≤NBEND.

Appendix 1: Sample Output From Programs

The sample output following is a set of computer printout pages obtained from running the PERMU and CONST/RECVRY programs. The board input data consisted of a set of 10 boards from the 14 Q.I.U. (3.5-inch) board width class. Five boards, numbered 291-295, were grade 3 Common with a length of 768 Q.I.U. (16 feet), and five boards, numbered 301-305, were grade 4 Common with a length of 576 Q.I.U. (12 feet). The minimum acceptable length between defects was set at 36 Q.I.U. (9 inches). Only those cutting combinations which resulted in a total cut (width) greater than 8 Q.I.U. and less than or equal to 14 Q.I.U. (total board width) were evaluated. Cutting combinations evaluated included (numbers in Q.I.U.), (4, 8), (8, 4), (12). The only other possible combination (4, 4, 4) was excluded to decrease the number of 1-inch-wide cuttings.

PERMU Output

The first line is a summary of the input values assigned to the program control parameters IBWDT, NSIZE, NSWBL, and the array KUT.

IBWDT	= 46 Q.I.U.	Maximum width of sample boards, 11.5-inches
NSIZE	= 3	Number of cutting sizes to consider
NSWBL	= 4	Number of machine saw blades available
KUT(1)	= 4 Q.I.U.	Consider a 1-inch cutting
KUT(2)	= 8 Q.I.U.	Consider a 2-inch cutting
KUT(3)	= 12 Q.I.U.	Consider a 3-inch cutting
KUT(4)	= 0	Not used this run
KUT(5)	= 0	Not used this run

The total number of possible combinations for three sizes and four blades is the computed value 120. Only those combinations which can be made using four positions within the limits of the board are printed out for user consideration.

Column 1 of the output table is a combination (COMBO) number used to reference the cutting combination. Columns 2-7 contain cutting combinations. The number 6 is used to fill out the table, and has no significance as far as combinations are concerned. The numbers 1, 2, and 3 in the table are referenced to the cutting sizes stored in array KUT so that 1 = 4, 2 = 8, and 3 = 12 Q.I.U. The number in column 8 is the total units cut for the given cutting combination and is used as a test limit in program RECVRY. The table output is ordered by increasing values in column 8.

```
 46    3    4    4    8   12    0    0

NBR OF DIFFERENT CUT COMBINATIONS =   120

  1    1    6    6    6    6    6    4
  2    2    6    6    6    6    6    8
  4    1    1    6    6    6    6    8
  3    3    6    6    6    6    6   12
  5    2    1    6    6    6    6   12
  7    1    2    6    6    6    6   12
 13    1    1    1    6    6    6   12
  6    3    1    6    6    6    6   16
  8    2    2    6    6    6    6   16
 10    1    3    6    6    6    6   16
 14    2    1    1    6    6    6   16
 16    1    2    1    6    6    6   16
 22    1    1    2    6    6    6   16
 40    1    1    1    1    6    6   16
  9    3    2    6    6    6    6   20
 11    2    3    6    6    6    6   20
 15    3    1    1    6    6    6   20
 17    2    2    1    6    6    6   20
 19    1    3    1    6    6    6   20
 23    2    1    2    6    6    6   20
 25    1    2    2    6    6    6   20
 31    1    1    3    6    6    6   20
 41    2    1    1    1    6    6   20

 43    1    2    1    1    6    6   20
 49    1    1    2    1    6    6   20
 67    1    1    1    2    6    6   20
 12    3    3    6    6    6    6   24
 18    3    2    1    6    6    6   24
 20    2    3    1    6    6    6   24
 24    3    1    2    6    6    6   24
 26    2    2    2    6    6    6   24
 28    1    3    2    6    6    6   24
 32    2    1    3    6    6    6   24
 34    1    2    3    6    6    6   24
 42    3    1    1    1    6    6   24
 44    2    2    1    1    6    6   24
 46    1    3    1    1    6    6   24
 50    2    1    2    1    6    6   24
 52    1    2    2    1    6    6   24
 58    1    1    3    1    6    6   24
 68    2    1    1    2    6    6   24
 70    1    2    1    2    6    6   24
 76    1    1    2    2    6    6   24
 94    1    1    1    3    6    6   24
 21    3    3    1    6    6    6   28
 27    3    2    2    6    6    6   28

 29    2    3    2    6    6    6   28
 33    3    1    3    6    6    6   28
 35    2    2    3    6    6    6   28
 37    1    3    3    6    6    6   28
 45    3    2    1    1    6    6   28
 47    2    3    1    1    6    6   28
 51    3    1    2    1    6    6   28
 53    2    2    2    1    6    6   28
```

```
 55   1   3   2   1   6   6   28
 59   2   1   3   1   6   6   28
 61   1   2   3   1   6   6   28
 69   3   1   1   2   6   6   28
 71   2   2   1   2   6   6   28
 73   1   3   1   2   6   6   28
 77   2   1   2   2   6   6   28
 79   1   2   2   2   6   6   28
 85   1   1   3   2   6   6   28
 95   2   1   1   3   6   6   28
 97   1   2   1   3   6   6   28
103   1   1   2   3   6   6   28
 30   3   3   2   6   6   6   32
 36   3   2   3   6   6   6   32
 38   2   3   3   6   6   6   32

 48   3   3   1   1   6   6   32
 54   3   2   2   1   6   6   32
 56   2   3   2   1   6   6   32
 60   3   1   3   1   6   6   32
 62   2   2   3   1   6   6   32
 64   1   3   3   1   6   6   32
 72   3   2   1   2   6   6   32
 74   2   3   1   2   6   6   32
 78   3   1   2   2   6   6   32
 80   2   2   2   2   6   6   32
 82   1   3   2   2   6   6   32
 86   2   1   3   2   6   6   32
 88   1   2   3   2   6   6   32
 96   3   1   1   3   6   6   32
 98   2   2   1   3   6   6   32
100   1   3   1   3   6   6   32
104   2   1   2   3   6   6   32
106   1   2   2   3   6   6   32
112   1   1   3   3   6   6   32
 39   3   3   3   6   6   6   36
 57   3   3   2   1   6   6   36
 63   3   2   3   1   6   6   36
 65   2   3   3   1   6   6   36

 75   3   3   1   2   6   6   36
 81   3   2   2   2   6   6   36
 83   2   3   2   2   6   6   36
 87   3   1   3   2   6   6   36
 89   2   2   3   2   6   6   36
 91   1   3   3   2   6   6   36
 99   3   2   1   3   6   6   36
101   2   3   1   3   6   6   36
105   3   1   2   3   6   6   36
107   2   2   2   3   6   6   36
109   1   3   2   3   6   6   36
113   2   1   3   3   6   6   36
115   1   2   3   3   6   6   36
 66   3   3   3   1   6   6   40
 84   3   3   2   2   6   6   40
 90   3   2   3   2   6   6   40
 92   2   3   3   2   6   6   40
102   3   3   1   3   6   6   40
108   3   2   2   3   6   6   40
110   2   3   2   3   6   6   40
114   3   1   3   3   6   6   40
116   2   2   3   3   6   6   40
118   1   3   3   3   6   6   40
```

CONST Output

The first line is a statement of the input values assigned to the program control parameters LBTD = 36, NBSTR = 291, and NBEND = 305. The next 10 lines are the input data for the first board, followed by the computed defect area for three cutting sizes for that board. Complete output for all the test boards is printed out for the sample run. When a large number of boards is to be evaluated, complete output for only the first board in the input set is printed to reduce the number of output pages required. The remaining boards in the input set are indicated only by their ID, which contains the grade class, board number, number of defects in the board, and the overall coordinates of the board. The last line is a statement indicating the run was successfully completed, and gives the total number of boards processed.

```
MIN. LENGTH BETWEEN DEFECTS CONTROL FO
THIS RUN IS    36   291 -  305

  3 291          8
  0   0       14 768
 11 366       14 374
  0 411        7 421
  0 444        1 473
  4 451       12 463
  0 537        2 547
  0 574        3 582
  8 667       13 671
  3 697       13 710
    1     480     960    1896
    2     440    1120    1776
    3     292     824    1332
    4     260     760       0
    5     260     824       0
    6     380     824       0
    7     380     824       0
    8     220       0       0
    9     252       0       0
   10     252       0       0
   11     252       0       0
   12       0       0       0
   13       0       0       0
   14       0       0       0

  3 292          5
  0   0       14 768
  0 208        9 232
  4 299       13 316
  0 514        4 525
  1 533       10 550
  5 637       10 642
    1     240     656     984
    2     308     656     984
    3     328     656     984
    4     328     656       0
    5     252     504       0
```

```
  6     252     504       0
  7     252     504       0
  8     252       0       0
  9     252       0       0
 10     156       0       0
 11      68       0       0
 12       0       0       0
 13       0       0       0
 14       0       0       0

  3 293         7
  0   0        14 768
  0  31         3  37
  8 113        14 123
  2 508         7 514
  1 525         5 530
  0 543        14 544
  9 609        14 618
 10 711        14 716
   1     292     584    1164
   2     292     664    1164
   3     292     736    1164
   4     144     480       0
   5     144     480       0
   6     184     480       0
   7     220     480       0
   8     100       0       0
   9     100       0       0
  10     100       0       0
  11     100       0       0
  12       0       0       0
  13       0       0       0
  14       0       0       0

  3 294         5
  0   0        14 768
 10 245        14 252
  0 295        14 355
 10 359        14 381
  9 646        14 658
  9 708        14 717
   1     240     480    1368
   2     240     480    1368
   3     240     648    1368
   4     240     912       0
   5     240     912       0
   6     240     912       0
   7     324     912       0
   8     456       0       0
   9     456       0       0
  10     456       0       0
  11     456       0       0
  12       0       0       0
  13       0       0       0
  14       0       0       0

  3 295         7
  0   0        14 768
 11  75        14  84
  0 175         4 190
  5 431        12 439
  6 545        13 554
  8 661        14 669
  0 679         5 689
  0 737        10 768

   1     224     584    1200
   2     224     728    1200
   3     256     728    1200
   4     292     728       0
   5     232     680       0
   6     224     520       0
   7     224     520       0
   8     224       0       0
   9     260       0       0
  10     260       0       0
  11     136       0       0
  12       0       0       0
  13       0       0       0
  14       0       0       0

  4 301         7
  0   0        14 576
 11   0        14  26
  2  95         7 100
  0 146         5 153
  2 181         9 186
  7 322        11 327
  0 498         2 576
  3 547         9 555
   1     492    1024    1848
   2     492    1024    1848
   3     296     632    1260
   4     296     632       0
   5     316     840       0
   6     176     560       0
   7     176     560       0
   8     156       0       0
   9     260       0       0
  10     124       0       0
  11     124       0       0
  12       0       0       0
  13       0       0       0
  14       0       0       0

  4 302        12
  0   0        14 576
  0  40         5  47
  0 226         4 237
 10 281        14 293
  3 291         9 298
 12 307        14 346
  9 348        14 361
  9 384        14 391
  0 438         6 448
  6 475         9 479
  0 505         7 512
  0 544         6 576
 12 551        14 576
   1     424    1304    2592
   2     424    1304    3192
   3     424    1648    3192
   4     652    1728       0
   5     608    1640       0
   6     580    1984       0
   7     348    1376       0
   8     256       0       0
   9     256       0       0
  10     540       0       0
  11     540       0       0
  12       0       0       0
```

```
 13       0       0       0
 14       0       0       0

  4 303          4
  0   0         14 576
  2 161          7 167
  0 290          3 329
  6 420         14 476
  3 502         11 514
   1     228    1112    1668
   2     228    1112    1668
   3     228    1112    1668
   4     400     800       0
   5     400     800       0
   6     400     800       0
   7     400     800       0
   8     376       0       0
   9     376       0       0
  10     376       0       0
  11     376       0       0
  12       0       0       0
  13       0       0       0
  14       0       0       0

  4 304          8
  0   0         14 576
  9  84         14  93
  7 124         13 132
  0 208          9 222
  9 236         14 246
  0 305          3 312
  4 346         13 358
 11 466         14 472
  6 511         14 522
   1      84     688    1872
   2     268     688    1872
   3     268    1200    1872
   4     148     872       0
   5     180     920       0
   6     180     920       0
   7     436     920       0
   8     436       0       0
   9     460       0       0
  10     348       0       0
  11     348       0       0
  12       0       0       0
  13       0       0       0
  14       0       0       0

  4 305          5
  0   0         14 576
  1  48          5  54
  6 156         11 165
 11 320         14 328
 11 491         14 498
  0 517          3 576
   1     260     592    1296
   2     260     592    1296
   3     260     592    1296
   4      60     120       0
   5      60     240       0
   6      36     192       0
   7      36     192       0
   8      36       0       0
   9      96       0       0
  10      96       0       0
  11      96       0       0
  12       0       0       0
  13       0       0       0
  14       0       0       0

END-OF-RUN. TOTAL BOARDS PROCESSED =  1
```

RECVRY Output

The first line is a short title to describe the type of boards processed by the program, and a summary of input values assigned to the program control parameters LBTD = 36, LPRM = 8, NBSTR = 291, and NBEND = 305. Output consists of percent recovery for each individual board, percent total recovery for all boards, percent total recovery for grade 3 Common boards, percent total recovery for grade 4 Common boards, and a summary of the number of times each available cutting combination was selected for the individual boards.

Output for the first board, number 291, shows that combination number 5 generated the "best" recovery area. From the PERMU output sample, combination number 5 is a (2, 1) cutting or an 8 and 4 Q.I.U. cut. Next is a set of six numbers which position the saw kerfs for combination number 5. The first saw kerf is located at unit 0 of the board. Units 1 through 8 are used for the first cut (8 Q.I.U.). The second saw kerf is located at unit 9. Units 10, 11, 12, and 13 are used for the second cut (4 Q.I.U.) and the third saw kerf is located at unit 14. A saw kerf location of zero indicates a position adjacent to the bottom edge of the board. If the saw kerfs and cutting widths do not account for all available units in the board as shown by boards 292, 295, and 302, two adjacent saw kerfs of one unit each are indicated, and only the upper saw kerf location is printed. The total clear area recovered is 8,004 Q.I.U., the total area of the board is 10,752 Q.I.U. (14 x 768), and the percent recovery for the board is 74,442 (8,004/10,752 x 100). This format is repeated for each board in the input file.

```
TEST 4-INCH 10 BRDS MIN LGT=36  11/27/77
36     8  291  305


BOARD NBR =  291
COMBO NBR =    5
   0   9  14  15  16  17
AREA RECOVERED =    8004
AREA OF  BOARD =   10752
PRCNT RECOVERY = 74.4420

BOARD NBR =  292
COMBO NBR =    5
```

```
   0  10  15  16  17  18
AREA RECOVERED =    8492
AREA OF  BOARD =   10752
PRCNT RECOVERY = 78.9807

BOARD NBR =  293
COMBO NBR =    5
   0   9  14  15  16  17
AREA RECOVERED =    8532
AREA OF  BOARD =   10752
PRCNT RECOVERY = 79.3527

BOARD NBR =  294
COMBO NBR =    5
   0   9  14  15  16  17
AREA RECOVERED =    8280
AREA OF  BOARD =   10752
PRCNT RECOVERY = 77.0089

BOARD NBR =  295
COMBO NBR =    5
   0  10  15  16  17  18
AREA RECOVERED =    8496
AREA OF  BOARD =   10752
PRCNT RECOVERY = 79.0179

BOARD NBR =  301
COMBO NBR =    7
   0   5  14  15  16  17
AREA RECOVERED =    5860
AREA OF  BOARD =    8064
PRCNT RECOVERY = 72.6687

BOARD NBR =  302
COMBO NBR =    7
   0   6  15  16  17  18
AREA RECOVERED =    5112
AREA OF  BOARD =    8064
PRCNT RECOVERY = 63.3929

BOARD NBR =  303
COMBO NBR =    7
   0   5  14  15  16  17
AREA RECOVERED =    5884
AREA OF  BOARD =    8064
PRCNT RECOVERY = 72.9663

BOARD NBR =  304
COMBO NBR =    7
   0   5  14  15  16  17
AREA RECOVERED =    5908
AREA OF  BOARD =    8064
PRCNT RECOVERY = 73.2639

BOARD NBR =  305
COMBO NBR =    7
   0   5  14  15  16  17
AREA RECOVERED =    6460
AREA OF  BOARD =    8064
PRCNT RECOVERY = 80.1091


TOTAL AREA RECOVERED =    71028
TOTAL AREA OF BOARDS =    94080
PRCNT TOTAL RECOVERY = 75.4974
```

```
TOTAL AREA RECOVERED-3C =    41804
TOTAL AREA OF BOARDS-3C =    53760
PCNT RECOVERY BOARDS-3C = 77.7604


TOTAL AREA RECOVERED-4C =    29224
TOTAL AREA OF BOARDS-4C =    40320
PCNT RECOVERY BOARDS-4C = 72.4802


PRCNT RECOVERY PER CUTTING SIZE  BOARDS-3C
 26.68899   51.07143    0.00000    0.00000

PRCNT RECOVERY PER CUTTING SIZE  BOARDS-4C
 24.88095   47.59921    0.00000    0.00000

COMBO NBR   NBR TIMES USED
    5              5
    7              5

END OF RUN. BOARDS  291 -   305 PROCESSED
```

An example of the System and Program Control Cards for running program CONST/RECVRY which generated the sample output follows:

```
JLIMITS, CM55000, T30, PR30.  ACOUNT NBR., NAME.
FTN.
REQUEST, TAPE7, D0000, 01.    CONST OUPUT (DISK)
LGO.
REWIND (TAPE7,LGO)            RECVRY INPUT (DISK)
RFL(43000)
FTN.
LGO.
7/8/9
CONST Source Deck.
7/8/9
CONST Program Control Card (LBTD,NBSTR,NBEND).
Board Defect Data Cards (NDEF+3 Cards/Board).
7/8/9
RECVRY Source Deck.
7/8/9
RECVRY Program Control Card Type 1 (TITLE).
RECVRY Program Control Card Type 2 (LBTD, LPRM,
      NBSTR, NBEND).
6/7/8/9 END-OF-JOB Card.
If Programs CONST and RECVRY are to be run as two
separate programs, request TAPE7 to be a magnetic
tape output file from CONST and specify it as a tape
input file to Program RECVRY.
```

Appendix 2: Source Listings for Programs

Program PERMU

```
      PROGRAM PERMU
     1(INPUT,OUTPUT,TAPE5=INPUT,TAPE6=OUTPUT,TAPE1)

C CONVERSION OF PROG NAME J1 (BASIC) TO FORTRAN. THIS PROGRAM CONSTRUCTS
C THE PERMUTATION, COMBINATION TABLE FOR NSIZE(NBR OF BRD WDTH SIZES)
C AND NSWBL(NBR OF MACHINE SAW BLADES). INITIAL INPUT IS TAKEN FROM TWO
C CARDS. OUTPUT IS A PRINT LISTING AND IF DESIRED A TAPE FILE(TAPE1).
C D. MARKSTROM  10/72  RMFRES  BJE

C--INPUT CARD 1  (3I5)
C     IBWDT=BOARD WIDTH  14,30,46 UNITS
C     NSIZE=NBR OF DIFFERENT SIZES TO CONSIDER. MAX=5
C     NSWBL=NBR OF SAW BLADES FOR YOUR MACHINE. MAX=6
C--INPUT CARD 2  (5I5)
C     KUT(I)=SIZES FOR NSIZE SIZES ON CARD 1.   MAX=5

C--PROGRAM VARIABLE NAMES
C     P(I,J)=PERMUTATION ARRAY FOR 6 SAW BLADES, 5 CUTTING WIDTHS
C     C(I)=COMBINATION ARRAY FOR 6 SAW BLADES, 5 CUTTING WIDTHS
C     LSUM=TOTAL NBR OF DIFFERENT CUT COMBINATIONS IN ARRAY C(KK)
C     NSWB=SAW BLADE NBR., 1 TO NSWBL+1
C     NCMB=COMBINATION (COMBO) NBR., 1 TO 1023. (FOR 3 SIZES,5 BLADES)
C     KERF=ACCUMULATOR FOR 1/4-INCH SAW KERFS
C     MWDH=ACCUMULATOR FOR CUTTING WIDTHS IN 1/4-INCH UNITS

      INTEGER P(7,1023),C(10)
      DIMENSION KUT(10)
      REWIND 1

C--INITIALIZE ARRAYS AND VARIABLES
      DO 5 I=1,10
      C(I)=0
      KUT(I)=0
    5 CONTINUE
      DO 8 N1=1,7
      DO 7 N2=1,1023
      P(N1,N2)=0
    7 CONTINUE
    8 CONTINUE
      LSUM=0

C--READ AND PRINT OUT INPUT CARDS 1 AND 2. WRITE TAPE FILE 1 ID RECORD
      READ(5,100) IBWDT,NSIZE,NSWBL
  100 FORMAT(5I5)
      KK=NSWBL + 1
      DO 15 N1=1,KK
      DO 10 N2=1,1023
      P(N1,N2)=6
   10 CONTINUE
   15 CONTINUE
      READ(5,100) (KUT(I),I=1,5)
      WRITE(6,102) IBWDT,NSIZE,NSWBL,(KUT(I),I=1,5)
  102 FORMAT(1H1,3I5,5X,5I5,/)
      WRITE(1,103) NSIZE,(KUT(I),I=1,5)
  103 FORMAT(6I5)

C--DETERMINE COMBINATIONS FOR NSIZE CUTS AND KK SAW BLADES
      K=0
      C(2)=NSIZE
      LSUM=LSUM + NSIZE
      I=0
      DO 20 K=2,KK
      I=K + 1
      C(I)=NSIZE**K + C(I-1)
      LSUM=LSUM + NSIZE**K
   20 CONTINUE

      NCUT=C(I-1)
      WRITE(6,104) NCUT
  104 FORMAT(1H ,*NBR OF DIFFERENT CUT COMBINATIONS =*I6,/)

C--FILL ARRAY P FOR NSIZE CUTS AND KK SAW BLADES
      N=1
      I=0
      C(1)=1
      DO 50 NSWB=1,KK
      K=C(NSWB)
      I=NSWB - 1
      IF(I.EQ.0) KZ=1
      IF(I.EQ.0) GO TO 25
      KZ=NSIZE**I
      K=K + 1
   25 KCZ=K + KZ
      DO 30 NCMB=K,KCZ
      IF(NCMB.GT.1023) GO TO 35
      P(NSWB,NCMB)=N
   30 CONTINUE
   35 N=N + 1
      K=K + KZ
      IF(N.GT.NSIZE) GO TO 40
      IF(K.GE.LSUM) GO TO 45
      GO TO 25
   40 N=1
      GO TO 25
   45 N=1
   50 CONTINUE

C--COMBINE CUT WIDTH AND SAW KERF SELECTIONS AND DETERMINE MIN BOARD
C--WIDTH FROM WHICH CUT CAN BE MADE
      KERF=0
      MWDH=0
      DO 75 NCMB=1,1023
      DO 55 NSWB=1,KK
      L=P(NSWB,NCMB)
      IF(L.EQ.6) GO TO 60
      MWDH=MWDH + KUT(L)
      KERF=KERF + 1
   55 CONTINUE
      GO TO 70
   60 MSUM=MWDH + KERF

      IF(MSUM.LE.IBWDT) GO TO 65
      P(7,NCMB)=99
      GO TO 70
   65 P(7,NCMB)=MWDH
   70 KERF=0
      MWDH=0
   75 CONTINUE
C
C--PRINT OUT PERM-COMB TABLE, ARRAY P, OF POSSIBLE CUTS FROM A 8
C--4 UNITS(1-INCH) TO IBWDT UNITS WIDE.
      KTMP=0
      DO 85 N=4,IBWDT
      DO 80 NCMB=1,1023
      IF(P(7,NCMB).NE.N) GO TO 80
      MWDH=P(7,NCMB)
      KTMP=P(6,NCMB)
      IF(KTMP.NE.0) GO TO 78
      KTMP=6
   78 WRITE(6,106) NCMB,(P(I,NCMB),I=1,5),KTMP,MWDH
  106 FORMAT(1H ,8I5)
      WRITE(1,108) NCMB,(P(I,NCMB),I=1,5),KTMP,MWDH
  108 FORMAT(8I5)
   80 CONTINUE
   85 CONTINUE
C
      ENDFILE 1
      REWIND 1
      CALL EXIT
      END
```

ram CONST

```
ROGRAM CONST
NPUT,OUTPUT,TAPE5=INPUT,TAPE6=OUTPUT,TAPE7)

SION OF PROG NAME CONST (BASIC) TO FORTRAN. THIS PROGRAM INPUTS
L X,Y DEFECT COORDINATES(FROM  CARDS) AND OUTPUTS MODIFIED X,Y
NATES(ON FILE 7) USING A MIN LENGTH BETWEEN DEFECTS LIMITATION
IS CARD INPUT(VAR. LBTD). THE MODIFIED X,Y FOR DEFECTS IS INPUT
G RECVRY WHICH SELECTS THE CUT COMBO FOR EACH INDIVIDUAL BRD.
  MARKSTROM  10/72  RMFRES  BJE  MODF. 07/72

 CONTROL CARD (3I5)
TD=MIN. LENGTH BETWEEN DEFECTS CONTROL VARIABLE (IN UNITS)
STR=NBR OF THE BRD TO START ANALYSIS  EXP. 201
END=NBR OF THE BRD TO END ANALYSIS    EXP. 299

CARDS. BRD IDENT., BRD COORD., DEF COORD., END OF BRD INPUT.

 IDENTIFICATION CARD. ONE/BOARD (5X,I2,24X,I5,32X,I4)
RD=BOARD GRADE CODE
RD=BOARD NUMBER
EF=NUMBER OF DEFECTS IN BOARD
 COORDINATE CARD. ONE/BOARD (I3,1X,I3,5X,I3,1X,I3)
XS=BOARD X-DIR(WIDTH) START COORD. IBXS=0
YS=BOARD Y-DIR(LNGTH) START COORD. IBYS=0
XE=BOARD X-DIR(WIDTH) END   COORD. IBXE=14,30, OR 46
YE=BOARD Y-DIR(LNGTH) END   COORD. IBYE=576,672, OR 768
T COORDINATE CARD(S). NDEF/BOARD (I3,1X,I3,5X,I3,1X,I3)
XS=DEFECT X-DIR(WIDTH) START COORD. IDXS GE IBXS
YS=DEFECT Y-DIR(LNGTH) START COORD. IDYS GE IBYS
XE=DEFECT X-DIR(WIDTH) END   COORD. IDXE LE IBXE
YE=DEFECT Y-DIR(LNGTH) END   COORD. IDYE LE IBYE
F BOARD DATA CARD. ONE/BOARD (I3,1X,I3,5X,I3,1X,I3)
XS=999
YS=0
XE=0
YE=0
 OF DATA CARDS FOR ONE BOARD WILL CONTAIN NDEF+3 CARDS.

AM VARIABLE NAMES
 I,44)=TABLE OF START AND END DEFECT COORD. FOR A BRD. I=IBXE
CT(3)=ACCUMULATOR FOR DEFECT AREA FOR 3 CUTTINGS, 4-8-12 UNITS.
 1)=POINTER WHICH POSITIONS DEFECT COORD. IN TABLE T.  I=IBXE
T(3)=THREE CUTTING SIZES.  SET BY PROG STATEMENTS.
B(I,768)=BRD DIMENSION ARRAY FOR COMPUTER SIMULATION OF ALL
         DEFECTS IN A BRD. I=IBXE
ND(I)=MIN DEFECT COORD. FOR LWB SCAN OF DEFECT AREA.  I=IBXE
XD(I)=MAX DEFECT COORD. FOR LWB SCAN OF DEFECT AREA.  I=IBXE
S=LENGTH DEFECT START COORD. VALUE, USED TO X-OUT DEFECT IN LWB
E=LENGTH DEFECT END   COORD. VALUE, USED TO X-OUT DEFECT IN LWB
=WIDTH DEFECT COORD. VALUE,          USED TO X-OUT DEFECT IN LWB

 DIMENSION IS SET BY THE USER AND IS DETERMINED BY THE WIDTH
OF BOARDS TO BE PROCESSED. THIS HELPS TO REDUCE CORE STORAGE
REMENTS AND RUN COSTS.

TEGER T(14,44),DFCT(3),P(14)
MENSION KUT(3)
OMMON LWB(14,768),MIND(14),MAXD(14),LDS,LDE,NBRD,NX
WIND 7
ALIZE ARRAYS. SET THE UPPER LIMIT OF THE I INDEX TO IBXE.
RST=0
UNT=0
T(1)=3
T(2)=7
T(3)=11
CT(1)=0
CT(2)=0
CT(3)=0
 2 I=1,14
 2 J=1,768
B(I,J)=0
 4 I=1,14
 4 J=1,44
(I,J)=0
 6 I=1,14
1)=2
INPUT CONTROL CARD
AD(5,100) LBTD,NBSTR,NBEND
RMAT(3I5)
ITE(6,101) LBTD,NBSTR,NBEND
RMAT(1H1,5X,*MIN. LENGTH BETWEEN DEFECTS CONTROL FOR THIS RUN IS
I4,2X,I4,* - *,I4,/)

 8 I=1,14
ND(I)=900
XD(I)=0
BOARD ID CARD
AD(5,102) NGRD,NBRD,NDEF
RMAT(5X,I2,24X,I5,32X,I4)
(EOF(5)) 90,15
(NBRD.LT.NBSTR) GO TO 87
(NBRD.GT.NBEND) GO TO 90
ITE(6,104) NGRD,NBRD,NDEF
RMAT(1H0,I3,1X,I3,5X,I3)
BOARD COORD. CARD
AD(5,106) IBXS,IBYS,IBXE,IBYE
RMAT(I3,1X,I3,5X,I3,1X,I3)
 FILE 7 FOR RECVRY INPUT
ITE(7) NGRD,NBRD,NDEF
ITE(7) IBXS,IBYS,IBXE,IBYE
ITE(6,107) IBXS,IBYS,IBXE,IBYE
RMAT(1H ,I3,1X,I3,5X,I3,1X,I3)

C--SET BRD Y-DIR START COORD. = 1  IBYS
      IBYS=1
C--READ BOARD DEFECT COORD. CARD(S)
   20 READ(5,106) IDXS,IDYS,IDXE,IDYE
      IF(IDXS.EQ.999) GO TO 35
C     IF(KFRST.NE.0) GO TO 22
      WRITE(6,107) IDXS,IDYS,IDXE,IDYE
   22 LDS=IDYS + 1
      LDE=IDYE
      IF(IDXE.LE.IBXE) GO TO 25
      IDXE=IBXE
   25 KK=IDXE - 1
      IF(IDXS.EQ.0.AND.KK.EQ.0) GO TO 32
C--STORE DEFECT COORD. IN ARRAY T AND SIMULATE DEFECT IN ARRAY LWB
      DO 30 I=IDXS,KK
      N=I + 1
      K=P(N)
      T(N,K+1)=IDYS
      T(N,K+2)=IDYE
      P(N)=P(N) + 2
      NX=N
      CALL XOUT
   30 CONTINUE
      GO TO 20
C
   32 K=P(1)
      T(1,K+1)=IDYS
      T(1,K+2)=IDYE
      P(1)=P(1) + 2
      NX=1
      CALL XOUT
      GO TO 20
C
C--DETERMINE IF MIN LENGTH BETWEEN DEFECTS EXISTS. IF NO, BLOCK OUT
C--(X-OUT) CLEAR AREA BETWEEN DEFECTS IN ARRAY LWB.
   35 CONTINUE
      KEND=IBXE
      DO 50 N=1,KEND
      K=P(N)
      P(N)=P(N) + 1
      T(N,K+1)=IBYE
      T(N,K+2)=IBYE
      KK=P(N)
      DO 45 M=3,KK,2
      IF(T(N,M) - T(N,M-1).EQ.0) GO TO 45
      IF(T(N,M) - T(N,M-1).LT.LBTD) GO TO 40
      IF(T(N,M).EQ.IBYE) GO TO 45
      GO TO 45
   40 LDS=T(N,M-1) + 1
      LDE=T(N,M+1)
      NX=N
      CALL XOUT
   45 CONTINUE
      P(N)=2
   50 CONTINUE
C
C--SET INDEXS FOR BOARD SCAN TO FIND DEFECT AREAS
      DO 85 N=1,KEND
      KK=0
      IS=N
      DO 80 K=3,5
      I=K - KK
      KK=KK + 2
      IE=N + KUT(I)
      LIMIT=IBXE - KUT(I)
      IF(N.GT.LIMIT) GO TO 80
C
C--FIND MIN-MAX DEFECT COORD. FOR BOARD SCAN. IF MAXD(M)=0, NO DEFECTS
C--FOR RANGE OF SCAN.
C
      DO 54 M=IS,IE
      IF(MAXD(M).EQ.0) GO TO 54
      GO TO 56
   54 CONTINUE
      GO TO 80
   56 IBYS=MIND(IS)
      IBYE=MAXD(IS)
      DO 60 M=IS,IE
      IF(MIND(M).LT.IBYS) IBYS=MIND(M)
      IF(MAXD(M).GT.IBYE) IBYE=MAXD(M)
   60 CONTINUE
C
C--MAKE X,Y SCAN OF BOARD ARRAY LWB TO FIND DEFECT AREA. IF DEFECT FOUND
C--ACCUMULATE DEFECT AREA IN DFCT(I).
      NCLRY=0
      DO 75 J=IBYS,IBYE
      DO 65 M=IS,IE
      IF(LWB(M,J).EQ.NBRD) GO TO 68
   65 CONTINUE
      NCLRY=NCLRY + 1
      GO TO 75
C--TEST FOR MIN DISTANCE BETWEEN DEFECTS IN LENGTH(Y) DIRECTION
   68 IF(NCLRY.EQ.0) GO TO 70
      IF(NCLRY.GE.LBTD) NCLRY=0
      IF(NCLRY.GE.LBTD) GO TO 70
      MULT=KUT(I) + 1
      IADD=NCLRY * MULT
      DFCT(I)=DFCT(I) + IADD
      NCLRY=0
C
   70 DFCT(I)=DFCT(I) + KUT(I) + 1
   75 CONTINUE
   80 CONTINUE
      P(1)=2
C
```

```
C--LIST DEFECT AREAS FOR FIRST BOARD AND WRITE FILE 7 FOR ALL BOARDS
C--FOR RECVRY INPUT.  BRANCH AND DO NEXT BOARD.
C      IF(KFRST.NE.0) GO TO 82
       WRITE(6,108) N,DFCT(1),DFCT(2),DFCT(3)
  108 FORMAT(1H ,I4,3(2X,I5))
   82 WRITE(7) DFCT(1),DFCT(2),DFCT(3)
       DFCT(1)=0
       DFCT(2)=0
       DFCT(3)=0
   85 CONTINUE
       KOUNT=KOUNT + 1
       KFRST=1
       GO TO 10
C
   87 KRECS=NDEF + 2
       DO 88 NSKP=1,KRECS
       READ(5,106) IDUM1,IDUM2,IDUM3,IDUM4
   88 CONTINUE
       GO TO 12
C
   90 WRITE(6,110) KOUNT
  110 FORMAT(1H0,5X,*END-OF-RUN. TOTAL BOARDS PROCESSED =*I4)
       ENDFILE 7
       REWIND 7
       END

       SUBROUTINE XOUT
C
C ROUTINE GO SUB 490 FROM PROG CONST (BASIC)
C THIS ROUTINE SIMULATES THE BRD DEFECT AREAS BY STORING THE BRD NUMBER
C (NBRD) IN ALL X,Y LOCATIONS OF A DEFECT. IT IS X-ING OUT, OR BLOCKING
C OUT THE AREA OF DEFECT AS SPECIFIED BY THE INDICATORS NX,LDS, AND LDE.
C MAX AND MIN DEFECT LIMITS IN THE Y DIRECTION ARE ALSO DETERMINED.
C
       COMMON LWB(14,768),MIND(14),MAXD(14),LDS,LDE,NBRD,NX
       DO 10 I=LDS,LDE
       LWB(NX,I)=NBRD
   10 CONTINUE
C
       IF(LDE.GT.MAXD(NX)) MAXD(NX)=LDE
       IF(LDS.LT.MIND(NX)) MIND(NX)=LDS
       RETURN
       END
```

ram RECVRY

```
ROGRAM RECVRY
NPUT,OUTPUT,TAPE5=INPUT,TAPE6=OUTPUT,TAPE7)

RSION OF PROG NAME GOOD1 (BASIC) TO FORTRAN. THIS PROGRAM INPUTS
ODIFIED X,Y BOARD COORDINATES (DEFECT AREA) FROM FILE TAPE7
ATED IN PROG CONST AND OUTPUTS THE BEST CUT TO MAXIMIZE RECOVER-
AREA FOR INDIVIDUAL BOARDS. THE PERMU-COMBO TABLE TO BE USED TO
ATE SELECTED BRD SIZES IS CODED IN DATA ARRAY KPCT. THESE VALUES
CHANGE DEPENDING ON BRD SIZE AND A NEW DATA LIST MUST BE INSERTED
URCE DECK.  D. MARKSTROM  10/72  RMFRES  BJE  MODF. 06/72

 CONTROL CARD TYPE 1 (4A10)
TLE(I)=IDENTIFICATION CARD FOR RUN

 CONTROL CARD TYPE 2 (4I5)
TD=MIN. LENGTH BETWEEN DEFECTS, SAME AS IN PROG CONST.
RM=LOWER LIMIT OF COMBINED CUTTINGS TO BE CONSIDERED FROM THE
    PERMU-COMBO SETS IN ARRAY KPCT. CUTTINGS GT LPRM ARE USED
    TO EVALUATE BEST FIT UNTILL A STOP INDICATOR, 999 IS FOUND.
STR=NBR OF THE BRD TO START ANALYSIS  EXP. 201
END=NBR OF THE BRD TO END ANALYSIS    EXP. 299

AM VARIABLE NAMES.

IZE=NBR OF CUTTING SIZES TO CONSIDER  MAX OF 5
T(I)=CUT SIZES IN QTR UNITS FOR NSIZE CUTS  EXP. 4,8,12,0,0
RD=BRD GRADE CODE
RD=BRD NUMBER
EF=NBR OF DEFECTS IN BRD
XS=BRD X-DIR(WIDTH) START COORD. IBXS=0
YS=BRD Y-DIR(LNGTH) START COORD. IBYS=0
XE=BRD X-DIR(WIDTH) END   COORD. IBXE=14,30,OR 46
YE=BRD Y-DIR(LNGTH) END   COORD. IBYE=576,672,OR 768
MB=COMBINATION(COMBO) NUMBER
S1=COMBO CUT SIZE 1     CODE 1=4, 2=8, 3=12 UNITS
S2=COMBO CUT SIZE 2     CODE 1=4, 2=8, 3=12 UNITS
S3=COMBO CUT SIZE 3     CODE 1=4, 2=8, 3=12 UNITS
S4=COMBO CUT SIZE 4     CODE 1=4, 2=8, 3=12 UNITS
S5=COMBO CUT SIZE 5     CODE 1=4, 2=8, 3=12 UNITS
S6=COMBO CUT SIZE 6     CODE 1=4, 2=8, 3=12 UNITS
CUT=TOTAL UNITS CUT FOR COMBO NCMB(SAWKERFS NOT INCLUDED)

EAR(I,J)=WORK ARRAY TO DETERMINE CLEAR AREA OF BOARD
RSZ(I,J)=ARRAY TO ACCUMULATE RECOVERY PER BOARD GRADE AND SIZE
MBN(I)=ARRAY OF SELECTED COMBO NBRS
RD(I)=TOTAL AREA RECOVERED BY GRADE
RD(I)=TOTAL AREA OF BOARDS BY GRADE

TEGER CLEAR(6,50),RGRSZ(5,6),SCMBN(130),TITLE(4),P1,P2,P3,P4,P5,
,CN
MENSION KUT(9),IGRD(9),JGRD(9),KSZE(6)
MENSION KPCT(56)

LIST STATEMENTS. KPCT IS DEPENDENT ON SIZE OF BRDS EVALUATED.
DE ONE MORE COMBO SET THEN DESIRED TO TERMINATE SEARCH WITH
(KPCT(IDX)) SET = 999. KPCT IS FOR IBXE=14 BOARD WIDTH.

TA KSZE/3,4,8,12,0,0/
TA KPCT/1,1,6,6,6,6,6,4,2,2,6,6,6,6,6,6,8,4,1,1,6,6,6,6,8,3,3,6,6,
6,6,12,5,2,1,6,6,6,6,12,7,1,2,6,6,6,6,6,12,999,1,1,1,1,1,1,99/

OUT ARRAYS AND READ CONTROL CARDS 1 AND 2
=0
AR=0
AB=0
LT=1
WIND 7
 2 I=1,6
 2 J=1,50
EAR(I,J)=0
 4 I=1,5
 4 J=1,6
RSZ(I,J)=0
 6 I=1,130
MBN(I)=0
 10 I=1,9
T(I)=0
RD(I)=0
RD(I)=0
AD(5,100) TITLE
RMAT(4A10)
AD(5,102) LBTD,LPRM,NBSTR,NBEND
RMAT(4I5)
ITE(6,104) TITLE,LBTD,LPRM,NBSTR,NBEND
RMAT(1H1,9X,4A10,4I5,//)
IZE=KSZE(1)
 15 I=1,5
T(I)=KSZE(I+1)

NPUT GENERATED BY PROG CONST. ID, BRD COORD., DEFECT AREAS
(=1
AD(7) NGRD,NBRD,NDEF
EOF(7)) 90,25
AD(7) IBXS,IBYS,IBXE,IBYE
NBRD.LT.NBSTR) GO TO 27
NBRD.GT.NBEND) GO TO 90
 TO 28
=1

=IBXE
 30 J=1,M1
AD(7) CLEAR(1,J),CLEAR(2,J),CLEAR(3,J)
   30 CONTINUE
      IF(KSLT.EQ.0) GO TO 80
C
C--USING DEFECT AREAS FROM PROG CONST, COMPUTE CLEAR AREAS OF BOARD
      DO 40 I=1,NSIZE
      MULT=KUT(I)*IBYE
      M1=((IBXE-KUT(I))+1)
      DO 35 J=1,M1
      CLEAR(I,J)=MULT - CLEAR(I,J)
   35 CONTINUE
   40 CONTINUE
      GO TO 50
C
C     DO 45 J=1,IBXE
C     WRITE(6,112) J,CLEAR(1,J),CLEAR(2,J),CLEAR(3,J)
C 112 FORMAT(1H ,4I8)
C  45 CONTINUE
C
C--SELECT A CUTTING COMBINATION FROM ARRAY KPCT
   50 CONTINUE
   52 NCMB=KPCT(IDX)
      KKS1=KPCT(IDX+1)
      KKS2=KPCT(IDX+2)
      KKS3=KPCT(IDX+3)
      KKS4=KPCT(IDX+4)
      KKS5=KPCT(IDX+5)
      KKS6=KPCT(IDX+6)
      NTCUT=KPCT(IDX+7)
      IF(NTCUT.EQ.99) GO TO 75
      IDX=IDX+8
      IF(NTCUT.LE.LPRM) GO TO 52
      KX=IBXE - NTCUT
C
C--KX IS NBR OF SAW KERF CUTS WITHIN THE BOARD DIMENSIONS IBXS-IBXE
C--EVALUATE SELECTED CUTTING COMBINATION FOR MAX CLEAR AREA, STORE IN KA
      DO 70 N=1,KX
      I1=(KUT(KKS1) + N + 1)
      J1=I1 + (KX-N)
      KS=CLEAR(KKS1,N)
      DO 68 N1=I1,J1
      KS1=CLEAR(KKS2,N1) + KS
      I2=(KUT(KKS2) + N1 + 1)
      J2=I2 + (KX-((J1-I1)+N))
      DO 66 N2=I2,J2
      KS2=CLEAR(KKS3,N2) + KS1
      I3=(KUT(KKS3) + N2 + 1)
      J3=I3 + (KX-((J2-I2)+(J1-I1)+N))
      DO 64 N3=I3,J3
      KS3=CLEAR(KKS4,N3) + KS2
      I4=(KUT(KKS4) + N3 + 1)
      J4=I4 + (KX-((J3-I3)+(J2-I2)+(J1-I1)+N))
      DO 62 N4=I4,J4
      KS4=CLEAR(KKS5,N4) + KS3
      I5=(KUT(KKS5) + N4 + 1)
      J5=I5 + (KX-((J4-I4)+(J3-I3)+(J2-I2)+(J1-I1)+N))
      DO 60 N5=I5,J5
      KS5=CLEAR(KKS6,N5) + KS4
      IF(KS5.GT.KA) GO TO 85
   58 KS5=0
   60 CONTINUE
   62 CONTINUE
   64 CONTINUE
   66 CONTINUE
   68 CONTINUE
   70 CONTINUE
      GO TO 52


C
C--OUTPUT INDIVIDUAL BOARD RESULTS, PCNT RECOVERY BY BRD
   75 IF(KA.EQ.0) GO TO 80
      WRITE(6,116) NBRD
  116 FORMAT(1H ,9X,*BOARD NBR = *I4)
      WRITE(6,118) CN
  118 FORMAT(1H ,9X,*COMBO NBR = *I4)
      WRITE(6,120) P1,P2,P3,P4,P5,P6
  120 FORMAT(1H ,9X,6I4)
      WRITE(6,122) KA
  122 FORMAT(1H ,9X,*AREA RECOVERED =  *I6)
      KB=IBXE*IBYE
      WRITE(6,124) KB
  124 FORMAT(1H ,9X,*AREA OF  BOARD =  *I6)
      AR=FLOAT(KA)
      AB=FLOAT(KB)
      PR=(AR/AB) * 100.
      WRITE(6,126) PR
  126 FORMAT(1H ,9X,*PRCNT RECOVERY =*F8.4,/)
      P1=P1 + 1
      P2=P2 + 1
      P3=P3 + 1
      P4=P4 + 1
      P5=P5 + 1
      P6=P6 + 1
C
C--ACCUMULATE RESULTS BY GRADE AND CUTTING SIZES
      SCMBN(CN)=SCMBN(CN) + 1
      KSAB=KSAB + KB
      KSAR=KSAR + KA
      IGRD(NGRD)=IGRD(NGRD) + KA
      JGRD(NGRD)=JGRD(NGRD) + KB
      RGRSZ(NGRD,L1)=RGRSZ(NGRD,L1) + CLEAR(L1,P1)
      RGRSZ(NGRD,L2)=RGRSZ(NGRD,L2) + CLEAR(L2,P2)
      RGRSZ(NGRD,L3)=RGRSZ(NGRD,L3) + CLEAR(L3,P3)
      RGRSZ(NGRD,L4)=RGRSZ(NGRD,L4) + CLEAR(L4,P4)
      RGRSZ(NGRD,L5)=RGRSZ(NGRD,L5) + CLEAR(L5,P5)
      RGRSZ(NGRD,L6)=RGRSZ(NGRD,L6) + CLEAR(L6,P6)
```

```
C
   80 KA=0
      KSLT=1
      DO 82 I=1,6
      DO 82 J=1,50
   82 CLEAR(I,J)=0
      GO TO 20
C
   85 CN=NCMB
      KA=KS5

      P1=N - 1
      P2=N1 - 1
      P3=N2 - 1
      P4=N3 - 1
      P5=N4 - 1
      P6=N5 - 1
      L1=KKS1
      L2=KKS2
      L3=KKS3
      L4=KKS4
      L5=KKS5
      L6=KKS6
      GO TO 58
C
C--OUTPUT ALL BOARD RESULTS, PCNT RECOVERY BY GRADE, BY SIZE WITHIN GRD
   90 WRITE(6,200) KSAR
  200 FORMAT(1HO,9X,*TOTAL AREA RECOVERED = *I8)
      WRITE(6,202) KSAB
  202 FORMAT(1H ,9X,*TOTAL AREA OF BOARDS = *I8)
      AR=FLOAT(KSAR)
      AB=FLOAT(KSAB)
      PR=(AR/AB) * 100.
      WRITE(6,204) PR
  204 FORMAT(1H ,9X,*PRCNT TOTAL RECOVERY = *F8.4,/)
C
      WRITE(6,206) IGRD(3)
  206 FORMAT(1HO,9X,*TOTAL AREA RECOVERED-3C = *I8)
      WRITE(6,208) JGRD(3)
  208 FORMAT(1H ,9X,*TOTAL AREA OF BOARDS-3C = *I8)
      AR=FLOAT(JGRD(3))
      AB=FLOAT(IGRD(3))
      IF(AR.EQ.0.0) PR=0.0
      IF(AR.EQ.0.0) GO TO 92
      PR=(AB/AR) * 100.
   92 WRITE(6,210) PR
  210 FORMAT(1H ,9X,*PCNT RECOVERY BOARDS-3C = *F8.4,/)
C
      WRITE(6,212) IGRD(4)
  212 FORMAT(1HO,9X,*TOTAL AREA RECOVERED-4C = *I8)
      WRITE(6,214) JGRD(4)
  214 FORMAT(1H ,9X,*TOTAL AREA OF BOARDS-4C = *I8)
      AR=FLOAT(JGRD(4))
      AB=FLOAT(IGRD(4))
      IF(AR.EQ.0.0) PR=0.0
      IF(AR.EQ.0.0) GO TO 94
      PR=(AB/AR) * 100.
   94 WRITE(6,216) PR
  216 FORMAT(1H ,9X,*PCNT RECOVERY BOARDS-4C = *F8.4,/)
C
      WRITE(6,218)
  218 FORMAT(1HO,9X,*PRCNT RECOVERY PER CUTTING SIZE  BOARDS-3C*)
      IF(JGRD(3).EQ.0) GO TO 96
      AR=FLOAT(JGRD(3))
      AB=FLOAT(RGRSZ(3,1))

      PR1=(AB/AR) * 100.
      AB=FLOAT(RGRSZ(3,2))
      PR2=(AB/AR) * 100.
      AB=FLOAT(RGRSZ(3,3))
      PR3=(AB/AR) * 100.
      AB=FLOAT(RGRSZ(3,4))
      PR4=(AB/AR) * 100.
      GO TO 98
   96 PR1=0.0
      PR2=0.0
      PR3=0.0
      PR4=0.0
   98 WRITE(6,220) PR1,PR2,PR3,PR4
  220 FORMAT(1H ,7X,4(2X,F9.5))
C
      WRITE(6,222)
  222 FORMAT(1HO,9X,*PRCNT RECOVERY PER CUTTING SIZE  BOARDS-4C*)
      IF(JGRD(4).EQ.0) GO TO 140
      AR=FLOAT(JGRD(4))
      AB=FLOAT(RGRSZ(4,1))
      PR1=(AB/AR) * 100.
      AB=FLOAT(RGRSZ(4,2))
      PR2=(AB/AR) * 100.
      AB=FLOAT(RGRSZ(4,3))
      PR3=(AB/AR) * 100.
      AB=FLOAT(RGRSZ(4,4))
      PR4=(AB/AR) * 100.
      GO TO 142
  140 PR1=0.0
      PR2=0.0
      PR3=0.0
      PR4=0.0
  142 WRITE(6,220) PR1,PR2,PR3,PR4
C
      WRITE(6,224)
  224 FORMAT(1HO,9X,*COMBO NBR    NBR TIMES USED *)
      DO 144 KC=1,130
      IF(SCMBN(KC).EQ.0) GO TO 144
      WRITE(6,226) KC,SCMBN(KC)
  226 FORMAT(1H ,9X,I5,10X,I5)
  144 CONTINUE
C
C--END OF RUN. REWIND TAPE7, PRINT MESSAGE, CALL EXIT
C
      WRITE(6,228) NBSTR,NBEND
  228 FORMAT(1HO,9X,*END OF RUN. BOARDS*I5,* - *I5,* PROCESSED*)
      REWIND 7
      CALL EXIT
      END
```

ram DEFEDIT

```
ROGRAM DEFEDIT(INPUT,OUTPUT,TAPE5=INPUT,TAPE6=OUTPUT)

TO EDIT DATA CARDS FOR CUTUP-REPAIR-RECOVERY STUDY  D.MARKSTROM

IMENSION DLW(30),DLL(30),DUW(30),DUL(30),IDH(8)

EAD(5,200) IDH
ORMAT(8A10)
RITE(6,1) IDH
ORMAT(1HI,5X,8A10,/)
 AND CHECK HEADER CARD.
EAD(5,10) CLASS, NUMBD,NDEF
ORMAT(5X,R3,22X,I6,32X,I4)
F(EOF(5)) 100,9
F(CLASS .EQ. 3R 3C .OR. CLASS .EQ. 3R 4C)   GOTO 11
O TO 14
F(NDEF .LT. 1) GO TO 14
O TO 13
RITE(6,2) NUMBD
ORMAT(*0*,10X,*ERROR IN THE FIRST CARD OF BOARD *,I4)
 BOARD COORDINATE CARD. CHECK LWR COORD. LT UPR COORD..
EAD(5,20) PLW,PLL,PUW,PUL
ORMAT(F3.0,1X,F3.0,5X,F3.0,1X,F3.0)
F(PLW .GE. PUW .OR. PLL .GE. PUL) GO TO 46
F(PUW .NE. 14.)GO TO 21
O TO 25
F(PUW .NE. 30.)GO TO 22
O TO 25
F(PUW .EQ. 46.)GO TO 25
O TO 46
F(PUL .NE. 576.)GO TO 40
O TO 35
F(PUL .NE. 672.)GO TO 41
O TO 35
F(PUL .EQ. 768.)GO TO 35
RITE(6,47) NUMBD,CLASS,PLW,PLL,PUW,PUL
ORMAT(1HO,10X,*BOARD NBR.*I4,* CLASS *R3,* HAS AN ERROR IN THE BO
RD COORD. CARD*,2(2X,F5.0),2X,F5.0))
 DEFECT COORDINATE CARD(S).
O 36 I=1,NDEF
EAD(5,20) DLW(I),DLL(I),DUW(I),DUL(I)
ONTINUE
K LWR COORD. LT UPR COORD. AND FOR DEFECTS OUTSIDE BRD COORD..
O 60 I=1,NDEF
F(DLW(I)) 56,52,52
F(DLL(I)) 56,54,54
F(DLW(I).GT.PUW) GO TO 56
F(DUW(I).GT.PUW) GO TO 56
F(DLL(I).GT.PUL) GO TO 56
F(DUL(I).GT.PUL) GO TO 56
F(DLW(I).GE.DUW(I)) GO TO 56
F(DLL(I).GE.DUL(I)) GO TO 56
O TO 60
RITE(6,57) I,NUMBD,DLW(I),DLL(I),DUW(I),DUL(I)
ORMAT(1HO,10X,*DEFECT CARD*I3,* BOARD NBR.*I4,* IS IN ERROR*,
(2X,F5.0,2X,F5.0))
ONTINUE
 FOR OVERLAP OF DEFECTS
(NDEF-1) 3,3,62
=NDEF - 1
) 74 J=1,J1
=J + 1
) 74 K=J2,NDEF
(DUL(J)-DLL(K)) 74,64,64
(DLL(J)-DUL(K)) 66,66,74
(DUW(J)-DLW(K)) 74,68,68
(DLW(J)-DUW(K)) 70,70,74
RITE(6,72) J,NUMBD,DLW(J),DLL(J),DUW(J),DUL(J)
ORMAT(1HO,10X,*DEFECT CARD*I3,* BOARD NBR.*I4,* HAS OVERLAP*,
2X,F5.0,2X,F5.0))
NTINUE
 TO 3

NTINUE
LL EXIT
D
```

Program CTDFCT

```
      PROGRAM CTDFCT
     1(INPUT,OUTPUT,TAPE5=INPUT,TAPE6=OUTPUT,TAPE1)
C
C  PROG. TO WRITE BOARD DEFECT DATA CARDS ON TAPE(FILE 1) FOR INPUT TO PROG
C  CONST. A DUMMY RECORD,CONTAINING 999,0,0,0,IS WRITTEN AS AN END-OF-BOARD
C  INDICATOR. INPUT IS A SET OF DEFECT CARDS GROUPED BY BRD-WIDTH CLASS
C  SUCH AS ALL 4-INCH, 8-INCH, OR 12-INCH BRDS.
C  D.MARKSTROM  REPAIR STUDY  02/71  BJE
C
      DIMENSION LSTID(8)
C
      REWIND 1
      KDUMY=0
      KTREC=0
      KEND=0
      LAST=0
      NGRD=0
      NBRD=0
      NDEF=0
      IXS=0
      IYS=0
      IXE=0
      IYE=0
C--READ LIST ID CARD TO IDENTIFY OUTPUT (8A10)
      READ(5,100) LSTID
  100 FORMAT(8A10)
      WRITE(6,102) LSTID
  102 FORMAT(1H1,5X,8A10)
C
C  READ BRD DEFECT CARDS AND OUTPUT TO TAPE1. LIST FOR MASTER RECORD.
C
   10 READ(5,104) NGRD,NBRD,NDEF
  104 FORMAT(5X,I2,24X,I5,32X,I4)
      IF(EOF(5)) 900,15
   15 LAST=NBRD
      WRITE(1,106) NGRD,NBRD,NDEF,KDUMY
  106 FORMAT(4I4)
      WRITE(6,108) NGRD,NBRD,NDEF,KDUMY
  108 FORMAT(1HO,10X,4I5)
      KEND=NDEF + 1
      DO 20 I=1,KEND
      READ(5,110) IXS,IYS,IXE,IYE
  110 FORMAT(I3,1X,I3,5X,I3,1X,I3)
      WRITE(1,106) IXS,IYS,IXE,IYE
      WRITE(6,112) IXS,IYS,IXE,IYE
  112 FORMAT(1H ,10X,4I5)
   20 CONTINUE
      IXS=999
      IYS=0
      IXE=0
      IYE=0
      WRITE(1,106) IXS,IYS,IXE,IYE
      WRITE(6,112) IXS,IYS,IXE,IYE
      IXS=0
      KTREC=KTREC + KEND + 2
      GO TO 10
C
C  END OF CARD INPUT. TERMINATE RUN.
C
  900 ENDFILE 1
      REWIND 1
      WRITE(6,114) LAST,KTREC
  114 FORMAT(1HO,5X,*END-OF-RUN. NBR OF LAST BOARD ON FILE = *I4,* TOTAL
     1 RECS WRITTEN ON FILE =*I5)
      CALL EXIT
      END
```

Erickson, Bernard J., and Donald C. Markstrom.
1972. Predicting softwood cutting yield by computer. USDA For. Serv. Res. Pap. RM-98, 15 p. Rocky Mt. For. and Range Exp. Stn., Fort Collins, Colo.

A computer program, written in FORTRAN predicts the maximum yield of cuttings for softwood cut-up and edge- and end-gluing operation. The program calculates cutting recovery (given cutting width and length constraints and defect locations on the board), and locates ripping saw kerfs.

Keywords: Programming (computers), softwood cut-up, end and edge gluing, dimension stock.

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COMPUTER SIMULATION OF SNOWMELT WITHIN A COLORADO SUBALPINE WATERSHED

by Charles F. Leaf and Glen E. Brink

Abstract

A dynamic model which simulates snowmelt in Colorado subalpine watersheds for all combinations of aspect, slope, elevation, and forest cover composition and density is described. The model simulates winter snow accumulation, the energy balance, snowpack condition, and resultant melt in time and space. Detailed flow chart descriptions of the various components of the model and a program listing are presented.

Keywords: Computer models, coniferous forests, model studies, simulation analysis, snowmelt, watershed management.

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[1]*Central headquarters maintained at Fort Collins in cooperation with Colorado State University. Research reported here was conducted and partly financed in cooperation with the Division of Atmospheric Water Resources Management, Bureau of Reclamation, U.S. Department of the Interior.*

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Computer Simulation of Snowmelt Within a Colorado Subalpine Watershed

Charles F. Leaf and Glen E. Brink

The systems approach is a way to determine the probable effects of land management on the many interdependent hydrologic components in the Colorado subalpine forest. Accordingly, we are developing mathematical models to simulate the hydrology of this high-elevation ecosystem.

As a first step, we are modeling: (1) winter snow accumulation, (2) the energy balance, (3) snowpack condition, and (4) resultant melt in time and space under a variety of conditions. Combinations of aspect, slope, elevation, and forest cover composition and density are included. The computer program described was initially written by the Watershed Systems Development Unit at the Pacific Southwest Forest and Range Experiment Station (Willen et al. 1971). We have revised the original program to better represent conditions in the Rocky Mountain region. With this snowmelt model, we have simulated the probable effects of forest cover manipulation and additions to the winter snowpack through weather modification.

The model consists of three parts: (1) the determination of the form of precipitation (rain or snow), (2) the melting process, and (3) snowpack condition in terms of energy level and free water requirements. Shortwave and longwave radiation represent the energy available for snowmelt. In the forested environment, shortwave radiation reaching the pack is estimated by means of a transmissivity coefficient function, which depends on the density and composition of the forest cover (Miller 1959, Reifsnyder and Lull 1965). Radiation inputs are adjusted for slope and aspect (Frank and Lee 1966). Reflectivity of the snowpack is varied according to precipitation, the energy balance, and time (U.S. Army 1956).

The snowpack is assumed to behave as a dynamic heat reservoir; thus all elements in the snowmelt portion of the model are expressed in units of heat. The net external energy balance is computed at the snow surface. Rain and snow are converted from inches at the prevailing air temperature to equivalent gram-calories. Each precipitation event is added algebraically as a caloric-heat event to develop the heat reservoir or snowpack. Temperatures within the snowpack are computed using unsteady heat flow theory. The snowpack will yield melt water only when it has reached a zero energy deficit (snowpack temperature = 0° C) and its free water holding capacity is satisfied. Snowmelt rates after the pack is primed are governed primarily by the longwave and shortwave energy balances at the snow surface. The discussion which follows is a detailed flow chart description of the various components of the model. The model has been programed for the CDC 6400 computer[2] at Colorado State University.

Program Description

Program MELTMOD (Main Program)

The main program (fig. 1) makes no computations, but serves only to coordinate the flow of the program. Within the listing of the main program is included a dictionary of all variables that are available for use and cross referencing by the subroutines as well as the main program. (This allocation of computer memory for mutual access by many routines is designated "blank common.") Other dictionaries appear throughout the subroutines for variables used exclusively within those routines. Blank common is arranged so that additional variables may be added easily; by using a very extensive blank common, the routines were broken down into simpler logical units rather than one or two

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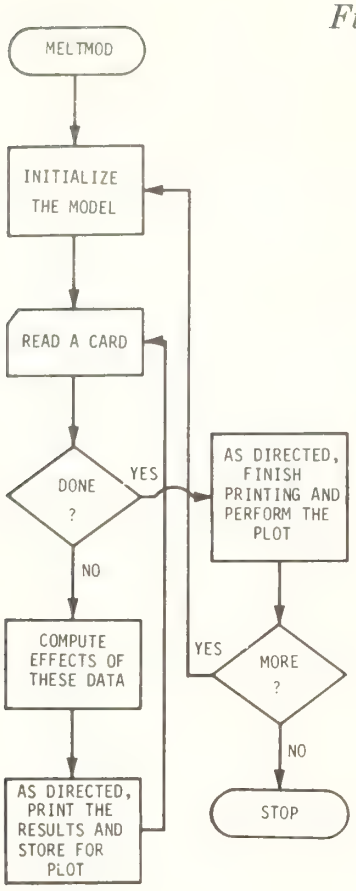
Figure 1.



large routines. The model contains 10 subroutines, discussed in the following order:

1. AFFECTS
2. CALIN
3. CALOSS
4. DIFMOD
5. GETREF
6. LINK
7. MIXTURE
8. RADBAL
9. RAINED
10. SNOWED

The parameters which describe the initial conditions in the model are solar radiation transmissivity coefficient, forest cover density, an initial pack temperature and water equivalent, and a threshold value for use in the reflectivity subroutine, GETREF. The data items supplied on a daily basis for the simulation are incoming shortwave radiation, daily maximum and minimum temperatures, observed water equivalent (optional), precipitation, and density of the snowpack (optional). Observed snowpack temperatures for use by the diffusion model, subroutine DIFMOD, are also optional, but recommended.

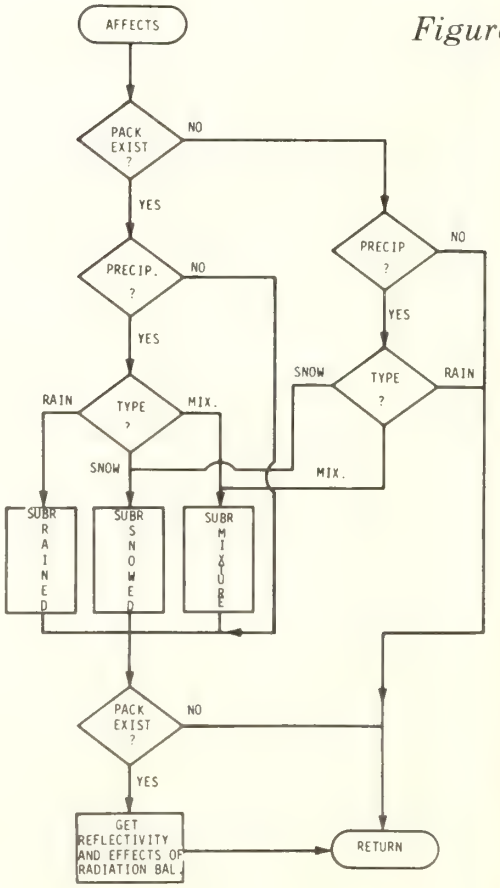
1. Subroutine AFFECTS (fig. 2)

The decisions necessary to compute th response to input data are started within th routine and continued in other routines. Th primary decision to be made here is the classif cation of a precipitation event. An event classified as follows:

a. If the daily minimum temperature is les than or equal to 32° F , **or** if the daily max mum temperature is less than or equal t 35° F , it is a snow event.
b. If the minimum temperature is greater tha 35° F , it is a rain event.
c. If the minimum temperature is betwee 32° F and 35° F , **and** the maximu temperature is greater than 35° F , it a mixture of rain and snow event. The tot precipitation is partitioned into rain an snow by the formula presented in subroutin MIXTURE.

The precipitation is added to th snowpack, and the caloric input or loss due t the precipitation is calculated. Effects on th snowpack are computed by subroutine

Figure 2



CALIN or CALOSS. Subroutines GETREF and RADBAL are then called to compute the reflectivity of the pack, and the influences of the radiation balance as computed from air temperature.

2. Subroutine CALIN (fig. 3)

This routine computes the effects of caloric input from either the radiation balance or from rainfall. A check is made to see if the input satisfies an exisiting calorie deficit, given by the equation

$$CALDEF = 203.2\ W_c \qquad [1]$$

where

CALDEF = heat deficit of the snowpack in calories, and

W_c = the "cold content" which represents the heat required to raise the snowpack to 0° C, in equivalent inches of water (U.S. Army 1960).

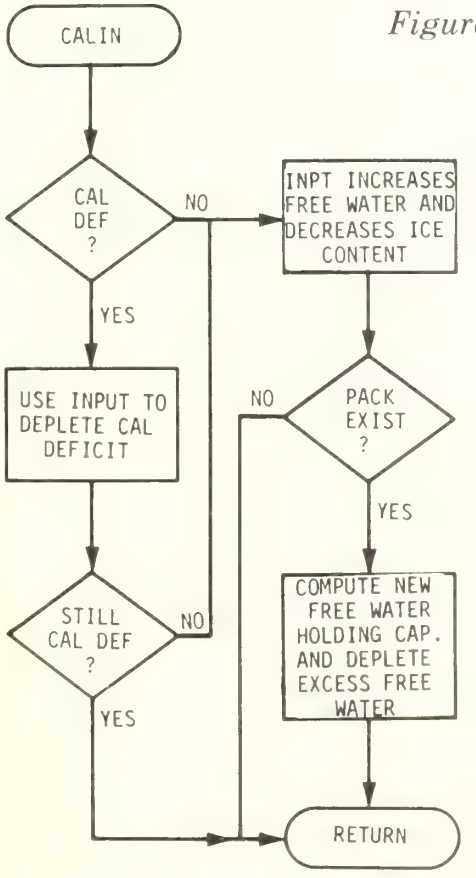


Figure 3.

If the input energy is not sufficient to make up the heat deficit, the only action taken is to adjust the pack temperature to compensate for the input. If the calorie deficit is satisfied and there is still sufficient input to generate melt, the melt is added to the free water content of the snowpack and deleted from the ice content. A new free water holding capacity is then computed (4 percent by weight of the ice content) and any excess free water is deleted from the pack.

3. Subroutine CALOSS (fig. 4)

This routine computes the effects of a loss of energy from the pack. The loss may be due to either a negative radiation balance (the back radiation exceeding incoming radiation) or "cold content" added by precipitation (fresh snow). The snowpack is first examined to see if any free water is present in the pack; if not, the calorie deficit is increased to compensate for the loss. If free water is present, the loss is used to freeze all or part of it (80 calories per cm. of free water). If the loss is more than sufficient to freeze all of the free water the remaining heat loss is used to create a calorie deficit (eq. 1).

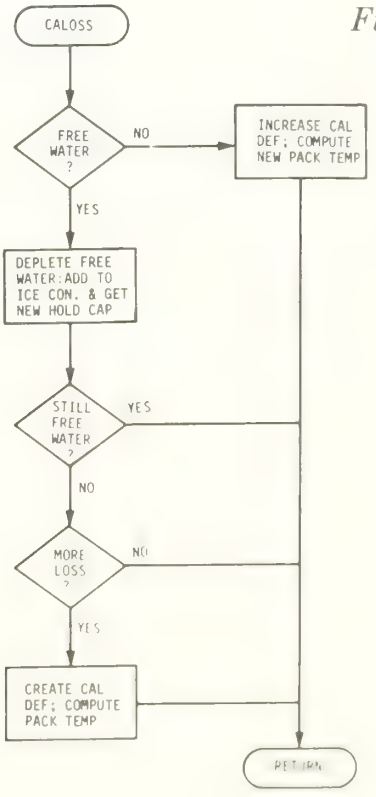


Figure 4.

4. Subroutine DIFMOD (fig. 5)

This routine controls the snowpack temperature through the winter months. Because the snowpack is typically below 0° C during much of the snow accumulation season, heat flow theory is used to index its thermal regime.

Total heat energy input to the snowpack is represented by air temperature measured 3 to 4 feet above the snow surface. The temperature in this boundary layer region is assumed to be an integration of all the processes involved, including incoming and outgoing radiation, wind, temperature, and humidity in the overlying airmass. The heat flow equation as solved by this routine is given by Quick (1967) and Riley et al. (1969):

$$k_s \frac{\partial^2 Ts}{\partial z^2} = c_s \rho_s \frac{\partial Ts}{\partial t} \qquad [2]$$

where

k_s = thermal conductivity in cal/°C/cm/sec,
c_s = specific heat in cal/gm/°C,
ρ_s = snowpack density in gm/cm^3
T_s = snowpack temperature in °C,
z = depth within snowpack (from surface) in cm., and
t = time in sec.

Equation [2] can be rewritten as:

$$\frac{\partial^2 Ts}{\partial z^2} = K_v \frac{\partial Ts}{\partial t} \qquad [3]$$

where

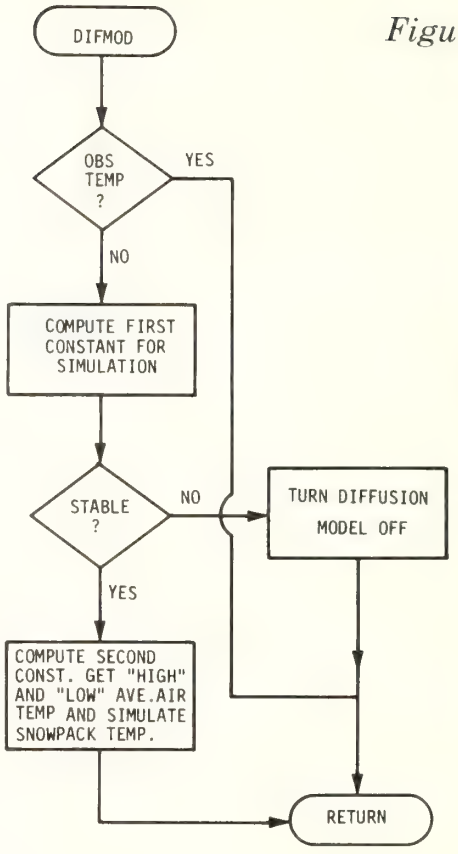
K_v = thermal diffusivity in cm^2/sec.

The thermal diffusivity is assumed to vary with density according to the relation proposed by Schwerdtfeger (1963):

$$K_v = \frac{2\, k_i}{(3\rho_i - \rho_s)c_i} \qquad [4]$$

where

k_i = thermal conductivity of ice in cal/°C/cm/sec.,
ρ_i = density of ice in gm/cm^3, and
c_i = specific heat of ice in cal/gm/°C.



Figure

The density is assumed to be constar throughout the pack, although it may var with time.

A finite difference solution for equatio [3] is obtained as follows (Smith 196 Richtmyer and Morton 1967):

Let

$$\frac{\partial u}{\partial t} = \sigma \frac{\partial^2 u}{\partial x^2} \quad \sigma = \text{const.} > 0 \qquad [$$

where equation [5] is the nondimensional for of equation [3]. (It should be noted that th number representing the depth of the pack 1.)

The forward difference approximatic to equation [5] is given by

$$\frac{u_{i,j+1} - u_{i,j}}{m} = \frac{u_{i+1,j} - 2u_{i,j} + u_{i-1,} }{h^2} \qquad [$$

where

$x = ih$, $(i = 0, 1, 2, \ldots)$
$t = jm$ $(j = 0, 1, 2, \ldots)$

Equation [6] can be written as:

$$u_{i,j+1} = u_{i,j} + \frac{mK_v}{h^2}(u_{i-1,j} - 2u_{i,j} + u_{i+1,j}) \quad [7]$$

which gives the explicit solution for the unknown temperature $u_{i,j+1}$ at the (i,j+1) th mesh point in terms of known temperatures along the j th time row. Hence, it becomes possible to calculate the unknown pivotal values of u along the first time row, t = m(fig. 6) in terms of known boundary and initial values along t = 0, then the unknown pivotal values along the second time row in terms of the calculated pivotal values along the first, and so forth.

Equation [7] utilizes the average air temperature (assumed to be the temperature of the surface of the snowpack), ground temperature, and temperature at the midpoint of the snowpack during the previous interval to simulate present snowpack temperature. The midpoint temperature is defined initially from observed data and simulated thereafter. The diffusion model has been found to be mathematically stable only for reasonably deep packs (≥4.7 inches of water equivalent). To insure stability in the model, each 24-hour period is divided into two 12-hour intervals and the result is averaged. The average air temperatures for each 12-hour interval are the "high average" (the mean of the maximum and daily mean temperatures) and the "low average" (the mean of the minimum and daily mean temperatures.)

Once the snowpack becomes isothermal, subroutine RADBAL computes the energy balance. Subroutine LINK determines when the diffusion model is to be used and when the radiation balance is to be used. The diffusion model may be initialized or readied by external controls or when the radiation balance creates a calorie deficit.

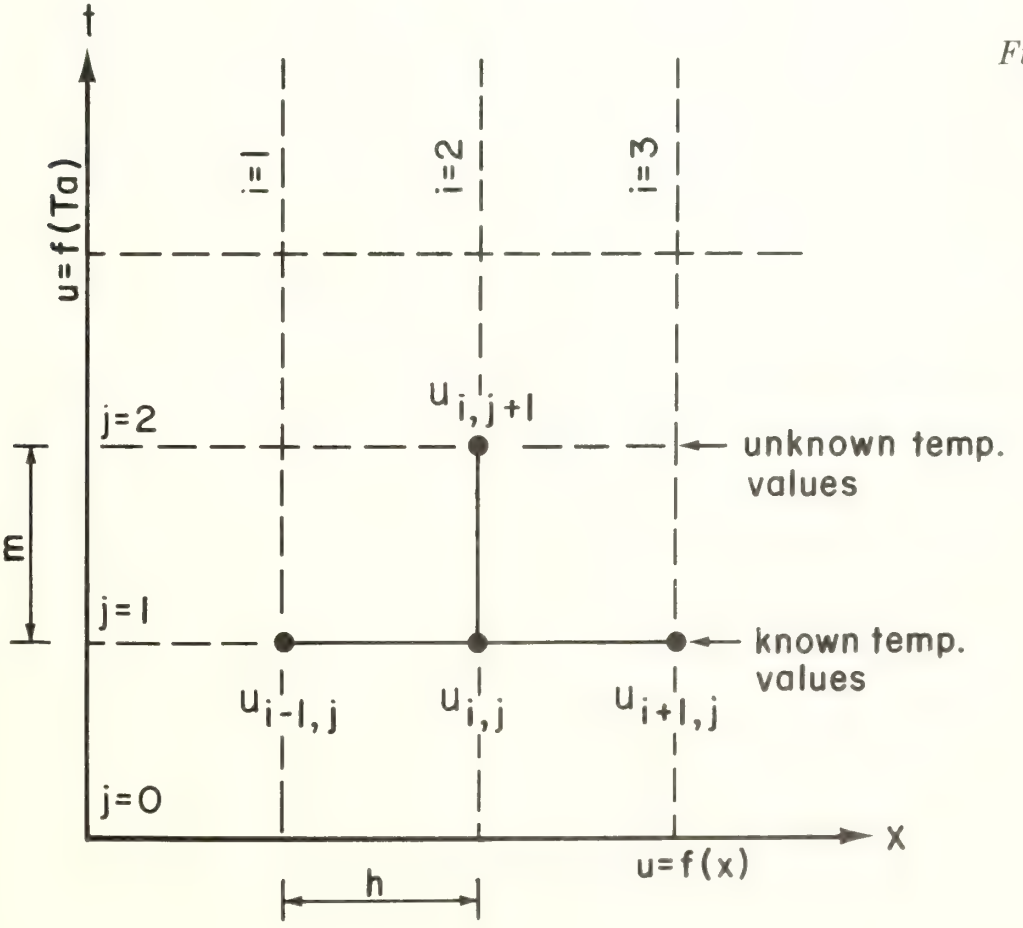


Figure 6.

5. Subroutine GETREF (fig. 7)

This routine selects the reflectivity for use in the radiation balance routine, RADBAL. In essence, there are two functions from which the reflectivity is selected: one for the accumulation phase of the snowpack and one for the melt phase (U.S. Army 1960). The reflectivity is assumed to start at a higher value and to decrease more slowly with time during accumulation than during the melt season. To determine which function to use, a check is made on the following conditions:

a. If no new snow was added to the pack during a given day, the length of time since fresh snow is increased by 1 day and the function used on the previous day is used again. The accumulation function computes reflectivity for 15 consecutive days. After 15 days, control shifts to the next lower value in the melt function, which computes reflectivity for an additional 26 days. After this period of time, the reflectivity is a constant 40 percent. The minimum value for the reflectivity in any case is assumed to be 40 percent.

b. If new snow has fallen on the pack, a further check is made to see if it was a "spring" or "winter" snow. This is determined by comparing the maximum daily temperature against a temperature threshold which varies according to elevation, forest cover, and aspect. If it is warmer than the threshold, no change is made and the control flows as explained in part a. If it is colder, indicating "winter" snow conditions, another check determines if the snowpack is isothermal and thus selects which function to use while re-initializing the day counter.

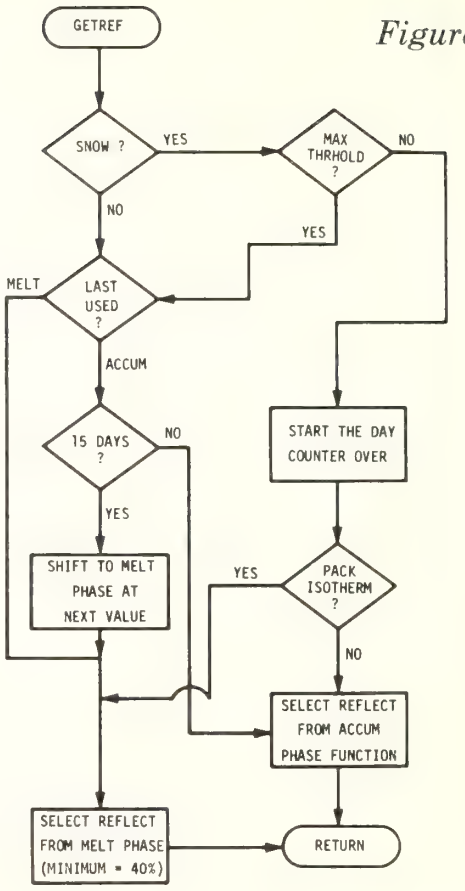


Figure 7

6. Subroutine LINK (fig. 8)

This routine is the interface between the thermal diffusivity model and the radiation balance routine. As discussed above, the diffusion model is used to control the snowpack temperature during the winter season. Air temperature is the driving variable in both routines, so they are somewhat related. The decision as to which method to use is basically dependent on whether the snowpack is still under "winter" conditions or "spring" conditions. The first check is to see if the radiation balance has simulated a caloric gain or loss from the pack. A loss requires a check to see if the pack has been isothermal with free water content ("spring") or if it has been cold ("winter"). If it was already cold, the diffusion model is used without further question. If the pack did contain free water, the loss is used to freeze it and, if a calorie deficit would be created, the diffusion model is re-initialized to isothermal conditions and the radiation balance is adjusted accordingly. In the event of a caloric gain, a check is made to see if the calorie deficit would be satisfied; if not, the diffusion model is used. If the deficit is satisfied, a further check is made to see if at least 0.05 inch of free water is generated; if not the diffusion model is set to isothermal conditions and control passes to the diffusion model. However, if sufficient free water is generated, the diffusion model is turned off and the radiation balance resumes full control.

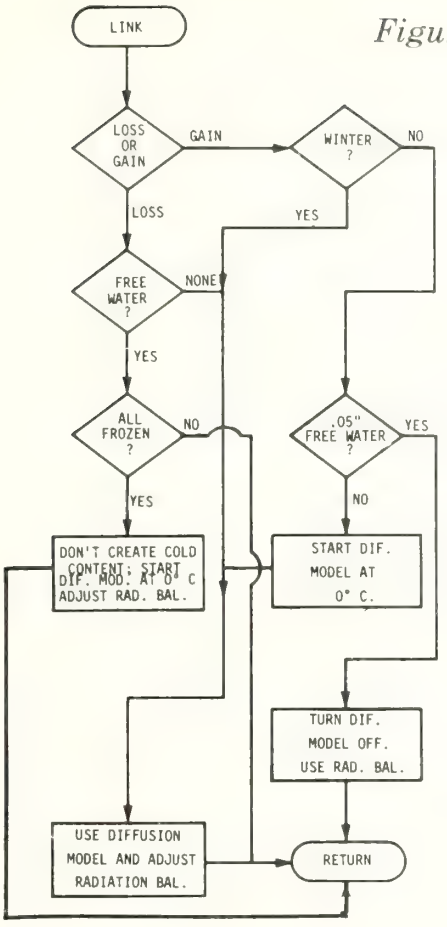


Figure 8.

7. Subroutine MIXTURE (fig. 9)

This routine partitions rain and snow precipitation components which fall on days when the maximum temperature is greater than 35° F and the minimum temperature is greater than 32° F, but less than 35° F. The partitioning is performed through the following equation:

$$SNOW = (PRECIP)\ (1 - B/A) \qquad [8]$$

where

B = the difference between the maximum temperature and 35°,
A = the difference between the maximum and minimum temperatures.

The "average" temperature for the snow period is computed as the mean of the minimum temperature and 35°, while that for rain is the mean for the maximum and 35°. Control then passes to the subroutines that make the computations for a snow event and a rain event.

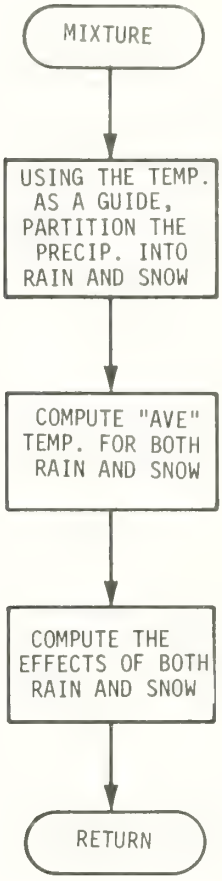

MIXTURE
USING THE TEMP. AS A GUIDE, PARTITION THE PRECIP. INTO RAIN AND SNOW
COMPUTE "AVE" TEMP. FOR BOTH RAIN AND SNOW
COMPUTE THE EFFECTS OF BOTH RAIN AND SNOW
RETURN

Figure 9.

8. Subroutine RADBAL (fig. 10)

This routine uses air temperature to compute the net radiation balance through the Stefan-Boltzmann function as follows:

$$L_P = \sigma T^4 \qquad [9]$$

where

L_P = potential longwave radiation at a given temperature,
σ = Stefan-Boltzmann constant for a 24-hour period: 1.17×10^{-7} (langleys)/(day)/(°K)$^{-4}$, and
T = temperature in °K.

The shortwave radiation component in the radiation balance is computed as a simple function of the transmissivity coefficient and

the cover density. Solar radiation is adjusted for slope and aspect, according to tables published by Frank and Lee (1966). The downward longwave component is computed by using the average air temperature in the Stefan-Boltzmann function according to the equations:

From sky to snow:

$$L_s = \alpha(1 - C_D)(1.17 \times 10^{-7})(T_A^4) \quad [10]$$

where

C_D = forest cover density expressed as a decimal,
T_A = ambient air temperature in °K, and
α = a factor (1 or 0.75) which accounts for clear or cloudy skies.

From forest cover to snow:

$$L_F = 1.17 \times 10^{-7} C_D T_F^4 \quad [11]$$

where

T_F = radiation temperature of foliage in °K.

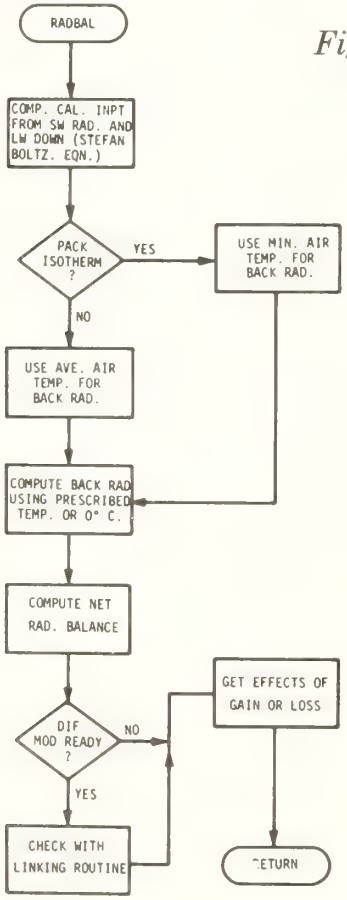

RADBAL
COMP. CAL. INPT FROM SW RAD. AND LW DOWN (STEFAN BOLTZ. EQN.)
PACK ISOTHERM ?
YES
USE MIN. AIR TEMP. FOR BACK RAD.
NO
USE AVE. AIR TEMP. FOR BACK RAD.
COMPUTE BACK RAD USING PRESCRIBED TEMP. OR 0° C.
COMPUTE NET RAD. BALANCE
GET EFFECTS OF GAIN OR LOSS
DIF MOD READY ?
NO
YES
CHECK WITH LINKING ROUTINE
RETURN

Figure 10.

The upward component (back radiation) is computed by using either the average daily air temperature ("winter" conditions) or the minimum air temperature ("spring" conditions) for the radiation temperature of the snowpack. In the case of the back radiation however, the temperature used must be less than or equal to 0° C. The equations used are

From snowpack to forest:

$$L_{SF} = 1.17 \times 10^{-7} C_D T_S^4 \quad [12]$$

where

T_S = radiation temperature of the snowpack in °K.

From snowpack to sky:

$$L_{SS} = (1 - C_D)(1.17 \times 10^{-7})(T_S^4) \quad [13]$$

Once the upward and downward components have been calculated, they are combined to get a net longwave balance as follows: if the skies are clear (no precipitation), only 75 percent of the downward longwave radiation given by equation [10] is combined with the back radiation from the snowpack (U.S. Army 1960). The radiation balance under the forest canopy is computed by equations [11] and [12]. During "winter" conditions, $T_F = T_S$ and $L_F = L_{SF}$. If there was precipitation, a check is made to see if it was snow. When there is snow, the longwave balance is assumed to be zero. Otherwise, under cloudy skies, the downward component and the back radiation are merely combined algebraically.

Once the net radiation is computed, the decision is made by the linking routine to use either the diffusion model or the radiation balance. The effects of the decision are then computed by either Subroutine CALIN or Subroutine CALOSS, depending upon the net gain or loss registered by the radiation balance.

9. Subroutine RAINED (fig. 11)

This routine computes the effects of a rain event on the snowpack according to the equation:

$$L_W = (C_R)(\Delta T)(P_R) \quad [14]$$

L_W = calorie gain due to rainfall

C_R = specific heat of water: 1 cal./gm/° C,

ΔT = difference between temperature (°C) at which rain falls and 0° C, and

P_R = amount of rainfall in centimeters.

If the pack is cold, the caloric input from the rain is used to satisfy all or part of the calorie deficit. If the input more than satisfies the deficit, the remainder is contributed as free water and the caloric input from that remaining is allowed to generate other melt. If the pack was already isothermal, the entire amount of rain is added to the pack as free water, and the calories contribute to the melt rate.

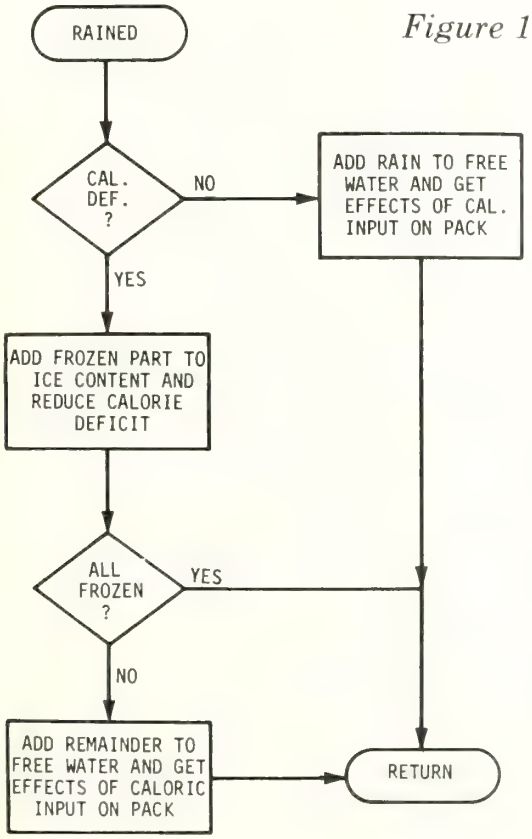

RAINED
CAL. DEF. ?
NO
ADD RAIN TO FREE WATER AND GET EFFECTS OF CAL. INPUT ON PACK
YES
ADD FROZEN PART TO ICE CONTENT AND REDUCE CALORIE DEFICIT
ALL FROZEN ?
YES
NO
ADD REMAINDER TO FREE WATER AND GET EFFECTS OF CALORIC INPUT ON PACK
RETURN

Figure 11.

10. Subroutine SNOWED (fig. 12)

This routine computes the effects of a snow event on the snowpack according to the equation

$$L_I = (C_S)(\Delta T)(P_S) \qquad [15]$$

where

L_I = calorie gain or loss due to snowfall,

C_S = specific heat of ice: 0.5 cal./gm/° C,

ΔT = difference between temperature (° C) at which snow falls and 0° C, and

P_S = water equivalent of snowfall in centimeters.

If the snow falls within the "warm" range of 32° to 35° F, no action is taken concerning the caloric loss. However, snow falling at lower temperatures increases the calorie deficit, and this change is accounted for.

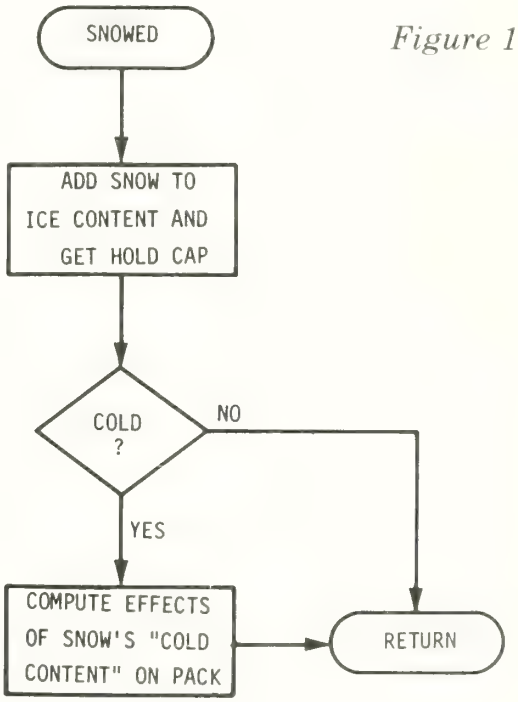


Figure 12.

Unlisted Routines

The routines listed below are not included in the flow-charted descriptions since they are merely utility routines for handling input, output, or internal processing of the information. They are not part of the model; rather, they are the necessary routines to implement the model on a digital computer.

INITIAL	RDPACK	STORE
PLOTTER	READER	WRITER

A complete listing of the snowmelt model as described above is included in appendix I.

Model Verification

The model has been tested on field data obtained from the 667-acre Deadhorse Creek watershed (fig. 13) at the Fraser Experimental Forest (Leaf 1971). Snowmelt rates at eight locations on Deadhorse Creek were reconstituted (fig. 14). Agreement between observed and simulated melt rates was good at all locations. The model is structured so that a minimum number of variables must be adjusted to obtain a satisfactory fit. In this case, only two variables were adjusted to obtain satisfactory agreement: (1) cover density (a vegetation type and composition parameter), and (2) a shortwave radiation transmissivity coefficient. Figure 15 compares observed and simulated snowpack accumulation and melt at the high-elevation north slope and low-elevation south slope sites on Deadhorse Creek in 1969. Table 1 is an example of the computer output.

With the cover density and transmissivity coefficients fixed as determined in 1969, the model has given good results in simulating snowmelt on Deadhorse Creek for the 1964-71 runoff seasons. Although it is a simplification of the real life system, the model produces reliable results.

Empirical studies have shown that various watershed management practices exert a significant effect on snowmelt rates and resultant streamflow. Because the model described here is a mechanistic representation of the snowmelt process, its careful use should enable the resource manager to better understand how a given management alternative will affect snowmelt **before** it is implemented. We believe it to be a useful tool for predicting the probable effects of land management practices on the timing and amount of snowmelt.

Figure 13. — Aerial view (foreground) of Deadhorse Creek watershed, Fraser Experiment Forest. The north-facing slope is in the lower lefthand corner of the photograph.

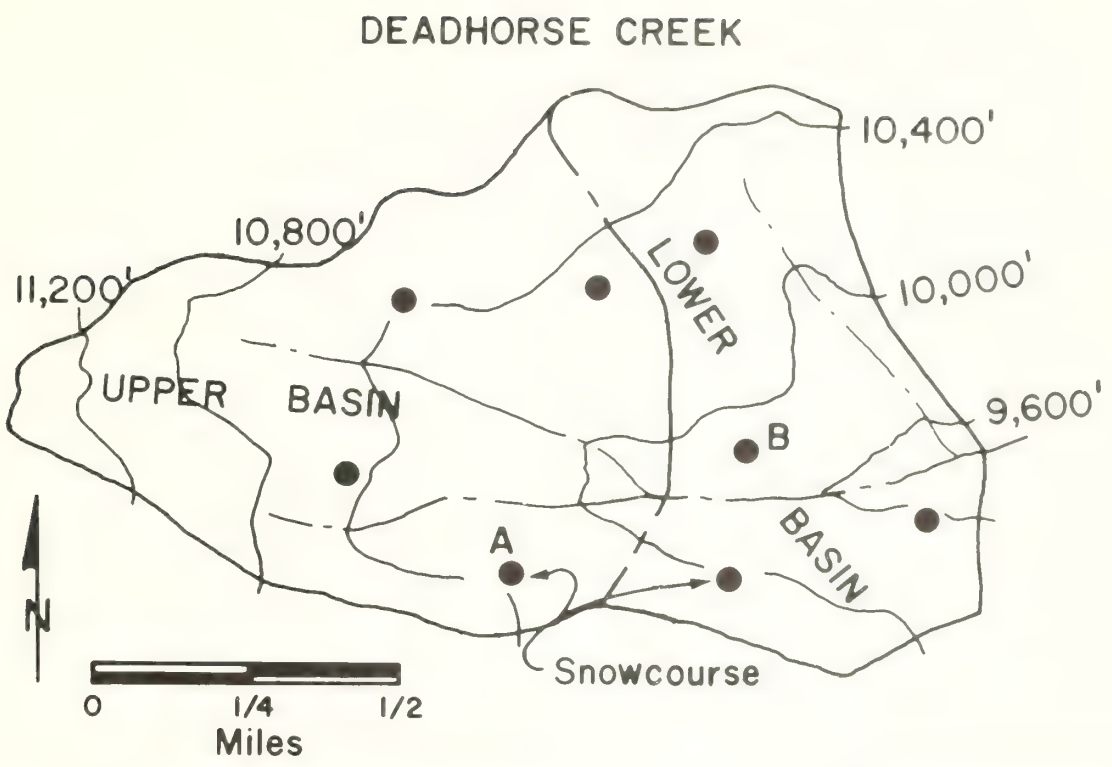


Figure 14. — Locations where field measurements were taken on Deadhorse Creek.

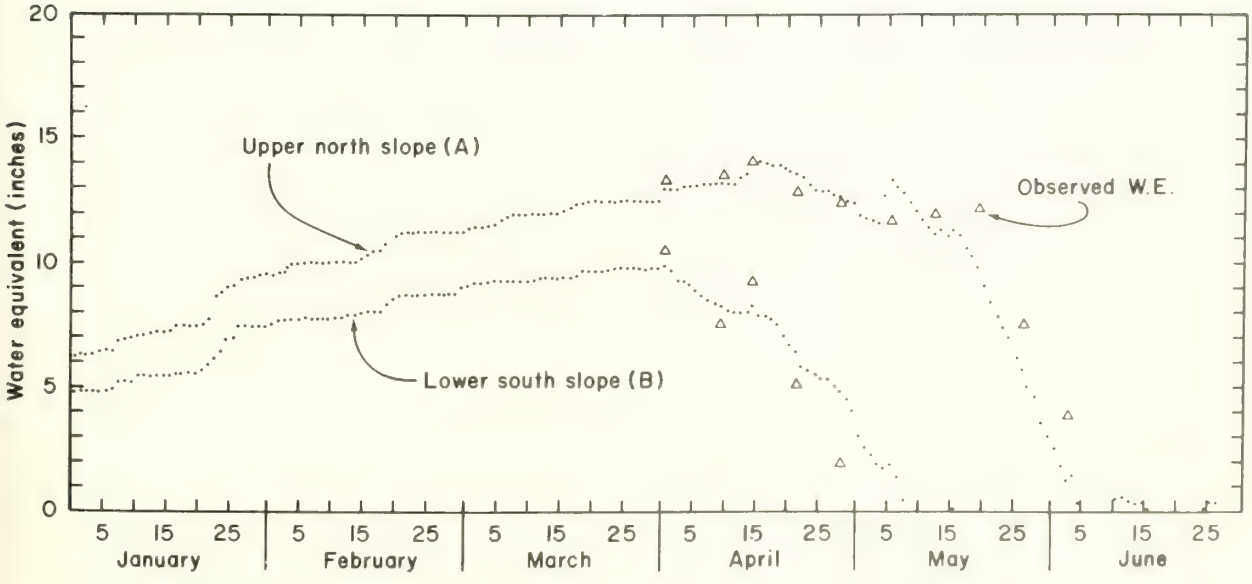


Figure 15. — Observed and simulated snowmelt on upper north (A) and lower south (B) slopes during 1969 snowmelt runoff season.

TABLE 1

SNOWMELT RUNOFF SIMULATION MODEL
FRASER EXPERIMENTAL FOREST, COLORADO
DEADHORSE CREEK, UPPER NORTH SLOPE

TRANSMISSIVITY COEFFICIENT = .25 COVER DENSITY = .55

DATE	TEMPERATURE (F) MAX	MIN	AVE	PRECIP (IN.) DAY	ACCUM	NET RAD (CAL) SHORT	LONG	ENERGY BAL (CAL)	SNOWPACK TEMP (C)	PREDICTED W.E. (IN)
4 [illegible]	30.0	12.0	21.0	0.11	13.45	[illegible]	-7.3	0.1	-1.0	13.45
[illegible] 69	32.0	13.0	[illegible]	0.00	13.45	13.5	-18.0	-4.5	-1.3	13.45
[illegible] 69	36.0	18.0	27.0	[illegible]	13.45	29.4	-49.5	-20.1	-2.4	13.45
4 [illegible]	40.0	23.0	31.5	0.00	13.45	30.7	-21.3	9.5	-1.9	13.45
[illegible]	45.0	27.0	36.0	0.00	13.45	25.7	-20.6	5.1	-1.6	13.45
4 [illegible]	34.0	25.0	29.5	.29	13.74	8.9	-5.6	2.8	-1.4	13.74
4 [illegible] 69	33.0	23.0	28.0	0.00	13.74	28.4	-22.4	6.1	-1.0	13.74
4 14 69	36.0	22.0	29.0	0.00	13.74	31.4	-30.8	.6	-1.0	13.74
4 15 69	40.0	20.0	30.0	.76	14.50	24.2	-30.8	-7.7	-1.4	14.50
4 16 69	28.0	15.0	21.5	.11	[illegible]	3.1	-.7	1.5	-1.3	14.61
4 17 [illegible]	32.0	15.0	23.5	[illegible]	14.61	22.9	-22.4	.6	-1.3	14.61
[illegible] 69	40.0	16.0	28.0	0.00	14.61	23.7	-24.7	-1.0	-1.3	14.61
4 19 69	44.0	[illegible]	33.0	0.00	14.61	34.3	-32.0	2.3	-1.2	14.61
4 [illegible] 69	47.0	17.0	[illegible]	0.00	14.61	38.6	-36.6	2.0	-1.1	14.61
4 [illegible]	53.0	30.0	41.5	0.00	14.61	40.3	-38.0	2.4	-1.0	14.61
4 [illegible] 69	45.0	33.0	39.0	0.00	14.61	34.1	-22.5	11.6	-.3	14.61
4 23 69	55.0	32.0	43.5	.52	15.13	37.4	-31.1	6.2	0.0	15.13
4 24 69	52.0	24.0	38.0	0.00	15.13	45.7	-1.0	44.7	0.0	15.13
4 [illegible] 69	[illegible]	9.0	16.5	0.00	15.13	36.5	-27.4	9.1	0.0	15.13
4 [illegible]	20.0	8.0	14.0	.14	15.27	16.9	0.0	15.1	0.0	15.27
4 27 69	27.0	[illegible]	17.5	0.00	15.27	33.0	-18.5	14.5	0.0	15.27
4 28 [illegible]	38.0	15.0	26.5	[illegible]	15.27	45.0	-11.2	33.7	0.0	15.27
4 [illegible]	42.0	22.0	32.0	0.00	15.27	48.3	-19.8	28.5	0.0	15.13
4 [illegible]	47.0	26.0	36.5	0.00	15.27	56.6	-18.5	38.1	0.0	14.94

ELEVATION 10500 FT.
ASPECT NE, SLOPE 35 PERCENT

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Appendix I: Complete Listing of Snowmelt Model

Program MELTMOD

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      PROGRAM MELTMOD (INPUT,OUTPUT,TAPE5=INPUT,TAPE6=OUTPUT)
C-----THIS IS A REWRITTEN VERSION OF -SNMELT-, A SNOW ACCUMULATION MODEL
C-----  DEVELOPED BY THE U. S. FOREST SERVICE AT BERKELEY.  THE RADIATION
C-----  BALANCE, AS DERIVED FROM AIR TEMPERATURE, SERVES AS THE MODEL
C-----  PARAMETERS AND CHARACTERISTICS.
C-----
C-----DICTIONARY OF BLANK COMMON
C-----
C     ACTDATE - THE DATE OF THE RECORDING OF THE VALUES IN -ACTUAL-
C     ACTUAL - THE OBSERVED SNOWPACK TEMPERATURES USED TO INITIALIZE THE
C                 DIFFUSION MODEL (SUBROUTINE DIFMOD).  LOCATIONS 1
C                 THROUGH 19 ARE THE OBSERVED TEMPERATURES AND LOCATION
C                 20 IS THE GROUND TEMPERATURE (-XX.X DEGREES C).
C                 LOCATION 21 IS THE DISTANCE BETWEEN THE MEASURED
C                 SNOWPACK TEMPERATURES (XX.X INCHES - USUALLY 6 IN.)
C     AVETEMC - THE DEGREES CENTIGRADE EQUIVALENT OF -AVETEMF-
C     AVETEMF - MEAN OR AVERAGE OF THE MAXIMUM AND MINIMUM TEMPERATURE
C                 IN DEGREES FARENHEIT
C     BASTEMF - BASE TEMPERATURE DEGREES FARENHEIT, RAIN TURNS TO SNOW
C     CALAIR - POTENTIAL LONGWAVE CALORIC INPUT AT AIR TEMPERATURE
C     CALDEF - THE CALORIE DEFICIT IS THE NUMBER OF CALORIES NEEDED
C                 TO BRING THE SNOWPACK TEMPERATURE TO ZERO DEGREES
C                 CENTIGRADE (NOTE SHOULD BE MADE THAT IT IS A POSITIVE
C                 QUANTITY)
C     CALORIE - CALORIES OF HEAT ABSORBED OR RELEASED BY THE SNOWPACK
C                 FROM THE NET RADIATION BALANCE
C     CALSNOW - POTENTIAL LONGWAVE CALORIC LOSS AT SNOW TEMPERATURE
C     COVDEN - THE COVER DENSITY IS THE FRACTION OF THE GROUND OR SNOW
C                 SURFACE SHADED FROM DIRECT SUNLIGHT OR RADIATION
C     DATE - THE DATE BEING PROCESSED IN MMDDYY FORMAT
C     DATES - AN ARRAY OF THE DATE BEING PROCESSED.  THE FIRST WORD IS
C                 THE MONTH, THE SECOND THE DAY, AND THE THIRD THE YEAR
C     DEN - THE SNOWPACK DENSITY READ FROM INPUT CARDS
C     DENSITY - THE DENSITY OF THE SNOWPACK USED IN THE DIFFUSION MODEL.
C                 IF -DEN- IS ZERO OR BLANK, -DENSITY- IS COMPUTED AS A
C                 FUNCTION OF THE PREDICTED WATER EQUIVALENT
C     DREADY = 0, DIFFUSION MODEL (SUBROUTINE DIFMOD) NOT INITIALIZED
C            = 1, DIFFUSION MODEL INITIALIZED AND READY FOR SNOWPACK
C                 TEMPERATURE SIMULATION
C     ENGBAL - THE TOTAL CALORIC INPUT TO OR LOSS FROM THE SNOWPACK
C                 DURING AN INTERVAL.  IT IS THE ALGEBRAIC SUM OF THE
C                 ENERGY INVOLVED WITH THE PRECIPITATION AND THAT OF
C                 THE RADIATION BALANCE, - CALORIE-
C     FOOTNOT - ARRAY OF FOOTNOTES TO BE PRINTED AT THE BOTTOM OF EACH
C                 PAGE.  TWO CARDS ARE READ, THE FIRST 130 CHARACTERS
C                 FORMING ONE LINE AND THE LAST 30 CHARACTERS FORMING A
C                 SECOND LINE
C     FREEWAT - THE FREE WATER BEING HELD BY THE SNOWPACK
C     HOLDCAP - THE FREE WATER HOLDING CAPACITY OF THE SNOWPACK
C                 (ASSUMED TO BE FOUR PERCENT OF THE WATER EQUIVLAENT)
C     IDATE - ARRAY FOR STORING THE DATES FOR PLOTTING
C     ISNOW - A SWITCH TURNED ON BY SUBROUTINE SNOWED WHEN THE PRECIP
C                 WAS SNOW AND THEN OFF BY SUBROUTINE GETREF AFTER
C                 COMPUTING THE REFLECTIVITY FOR THE GIVEN INTERVAL
C     ITABLE = 0, NO PRINTING OF TABULATED RESULTS FROM THE SIMULATION
C            = 1, PRINT THE TABULATED RESULTS FROM THE SIMULATION
C     KOUNT - COUNTER FOR THE NUMBER OF CARDS READ, MAXIMUM OF 372 DUE
C                 TO THE DIMENSIONS OF THE VARIABLES FOR STORING THE
C                 INFORMATION FOR PLOTTING
C     LASTUSD - AN INDICATOR USED IN SUBROUTINE GETREF TO DETERMINE
C                 WHICH REFLECTIVITY FUNCTION TO USE
C     LINES - THE LINE COUNTER FOR PAGE EJECTION
C     NEXTACT - A ONE COLUMN CODE (COL 70) ON THE INPUT CARDS TO
C                 INDICATE WHEN A CARD CONTAINING THE ACTUAL SNOWPACK
C                 TEMPERATURES IS TO BE READ.  WHEN COLUMN 70 IS NOT
C                 BLANK OR ZERO, CONTROL SHIFTS TO SUBROUTINE RDPACK
C                 WHICH THEN READS THE NEXT CARD
C     OBSWEQV - OBSERVED WATER EQUIVALENT OF THE SNOWPACK IN INCHES
C     PACKTEM - THE EFFECTIVE TEMPERATURE OF THE SNOWPACK
C     PARTICE - THE PORTION OF THE PREDICTED WATER EQUIVALENT THAT IS
C                 ICE.  THIS QUANTITY PLUS FREE WATER IS THE TOTAL
C                 PREDICTED WATER EQUIVALENT (-PREWEQV-)
C     PASTINT - NUMBER OF INTERVALS SINCE THE LAST INITIALIZATION OF THE
C                 REFLECTIVITY FUNCTION
C     PLOTOBS = 0, DO NOT PLOT THE OBSERVED WATER EQUIVALENT
C             1, PLOT THE OBSERVED WATER EQUIVALENT (OPERATIVE ONLY IF
C                -PLOTWE- IS TURNED ON)
C     PLOTWE = 0, DO NOT PLOT THE SIMULATION
C            = 1, PLOT THE SIMULATION, PRECIP, ETC.
C     PRECIP - OBSERVED PRECIPITATION IN INCHES
C     PREWEQV - PREDICTED WATER EQUIVALENT OF THE SNOWPACK IN INCHES
C     RADIN - RADIATION IN IS THE TOTAL INCIDENT SHORT WAVE RADIATION
C     RADLWN - NET LONG WAVE RADIATION IS THE ALGEBRAIC SUM OF THE LONG
C                 WAVE RADIATION FROM THE FOREST AND THE LONG WAVE
C                 RADIATION LOST BY THE SNOWPACK TO THE CANOPY
C     RADSWN - THE CALORIC INPUT TO THE PACK BY THE NET SHORT WAVE
C                 RADIATION
C     REFLECT - THE FRACTION OF RADIATION THAT IS REFLECTED BY THE SNOW
C                 AS DERIVED BY SUBROUTINE GETREF
C     SIMTEM1 - AN ARRAY USED PRIMARILY IN SUBROUTINE DIFMOD IN THE
C                 SIMULATION OF THE AVERAGE SNOWPACK TEMPERATURE.
C                 TO INSURE STABILITY OF THE DIFFUSION MODEL, THE
C                 DAY IS PARTITIONED INTO 12 HOUR INTERVALS, AS
C                 DISCUSSED IN SUBROUTINE DIFMOD.  THIS ARRAY STORES
C                 THE CONDITIONS PRESENT DURING THIS INTERVAL FOR USE
C                 IN THE SIMULATION ON THE NEXT INTERVAL.  LOCATION 1
C                 STORES THE AVERAGE AIR TEMPERATURE (ASSUMED TO BE
C                 THE SURFACE TEMPERATURE OF THE SNOWPACK), LOCATION 2
C                 IS THE SNOWPACK TEMPERATURE AT  . NODE MIDWAY
C                 BETWEEN THE SURFACE AND THE GROUND, AND LO
C                 THE GROUND TEMPERATURE.
C     SIMTEM2 = THE SNOWPACK TEMPERATURE AT THE MIDDLE NODE FO
C                 INTERVAL, AS SIMULATED BY SUBROUTINE DIFMO
C     SIMTEM3 = THE AVERAGE SNOWPACK TEMPERATURE FOR THIS INTE
C                 DERIVED BY SUBROUTINE DIFMOD
C     SNOMELT - MELT DELIVED IN INCHES FOR THE INTERVAL
C     SOBSEQV - ARRAY FOR STORING THE OBSERVED WATER EQUIVALEN
C                 PLOTTING
C     SPRECIP - ARRAY FOR STORING THE PRECIP FOR PLOTTING
C     SPREQV - ARRAY FOR STORING THE PREDICTED WATER EQUIVALEN
C     SUBTITL - ONE CARD SUBTITLE, SIMILAR TO -TITLE-
C     TCOEFF - THE TRANSMISIVITY COEFFICIENT USED TO ESTIMATE
C                 SHORT WAVE RADIATION REACHING THE SNOWPACK.
C                 REIFSNYDER AND LULL, RADIANT ENERGY IN RELA
C                 FORESTS, USFS TECH. BUL 1344, 1965.
C     TEMPMAX - THE MAXIMUM TEMPERATURE DURING THE INTERVAL IN
C                 FARENHEIT
C     TEMPMIN - THE MINIMUM TEMPERATURE DURING THE INTERVAL IN
C                 FARENHEIT
C     THRSHLD - THE THRESHOLD TEMPERATURE FOR DETERMINING WHET
C                 TO RE-INITIALIZE THE REFLECTIVITY FUNCTION
C                 THERE IS A SNOW EVENT.  IF THE MAXIMUM TEMP
C                 GREATER THAN THE THRESHOLD VALUE DO NOT RE-
C                 THE FUNCTION REGARDLESS OF THE PRECIPITATI
C     TITLE - ONE CARD TITLE (IF THE INFORMATION IS CENTERED (O
C                 IT WILL BE PROPERLY CENTERED ON THE PAGE)
C     TOTPREC - THE ACCUMULATED TOTAL PRECIPITATION IN INCHES
C     USEMEAN = 0, USE MAXIMUM AND MINIMUM TEMPERATURES AS REA
C             = 1, REPLACE THE MAXIMUM AND MINIMUM TEMPERATURE
C                 MEAN
C     XMAX - MAXIMUM OBSERVED OR PREDICTED WATER EQUIVALENT, U
C                 SCALING
C-----
      COMMON ACTDATE,ACTUAL(21),AVETEMC,AVETEMF
      COMMON BASTEMF
      COMMON CALAIR,CALDEF,CALORIE,CALSNOW,COVDEN
      COMMON DATE,DATES(3),DEN,DENSITY,DREADY
      COMMON ENGBAL
      COMMON FOOTNOT(16),FREEWAT
      COMMON HOLDCAP
      COMMON IDATE(372),ISNOW,ITABLE
      COMMON KOUNT
      COMMON LASTUSD,LINES
      COMMON NEXTACT
      COMMON OBSWEQV
      COMMON PACKTEM,PARTICE,PASTINT,PLOTOBS,PLOTWE,PRECIP,PRE
      COMMON RADIN,RADLWN,RADSWN,REFLECT
      COMMON SIMTEM1(3),SIMTEM2,SIMTEM3,SNOMELT,SOBSEQV(372),
     1       SPRECIP(372),SPREQV(372),SUBTITL(8)
      COMMON TCOEFF,TEMPMAX,TEMPMIN,THRSHLD,TITLE(8),TOTPREC
      COMMON USEMEAN
      COMMON XMAX
      INTEGER ACTDATE
      INTEGER DATE,DATES,DREADY
      INTEGER FOOTNOT
      INTEGER PASTINT,PLOTOBS,PLOTWE
      INTEGER SUBTITL
      INTEGER TITLE
      INTEGER USEMEAN
      COMMON/CONVERT/FIVE9TH,THIRTY2
      DATA FIVE9TH,THIRTY2/.5555555556,32.0/
C-----INITIALIZE THE MODEL AND READ THE PARAMETER CARDS
   10 CALL INITIAL
C-----READ A DATA CARD
   20 CALL READER (IEND)
C-----A BLANK CARD MAY BE USED TO SEPARATE SETS OF DATA
      IF(IEND.NE.0.OR.DATE.LE.0) GO TO 60
C-----SEE HOW THIS INTERVAL AFFECTS THE SIMULATION
      CALL AFFECTS
C-----IF THE TABLE IS BEING PRINTED, WRITE THIS LINE
      IF(ITABLE) 40,40,30
   30 CALL WRITER
C-----IF THE PLOT IS TO BE DONE, STORE THIS INFORMATION.  THEN
C-----  THE NEXT CARD
   40 IF(PLOTWE) 20,20,50
   50 CALL STORE
      GO TO 20
C-----ALL CARDS HAVE BEEN READ, SO PLOT THE SIMULATION AFTER W
C-----  THE FOOTNOTES ON THE LAST PAGE
   60 IF(ITABLE.NE.0) WRITE (6,910) FOOTNOT
  910 FORMAT(1H013A10/1X3A10)
      IF(PLOTWE.NE.0) CALL PLOTTER
C-----IF THE END OF FILE HAS NOT BEEN SENSED, GO ON TO THE NEX
C-----  DATA
      IF(IEND) 70,10,70
   70 STOP
      END
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Subroutine AFFECTS

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      SUBROUTINE AFFECTS
C-----DETERMINE THE EFFECTS OF THE DATA FROM THIS CARD
      COMMON ACTDATE,ACTUAL(21),AVETEMC,AVETEMF
      COMMON BASTEMF
      COMMON CALAIR,CALDEF,CALORIE,CALSNOW,COVDEN
      COMMON DATE,DATES(3),DEN,DENSITY,DREADY
      COMMON ENGBAL
      COMMON FOOTNOT(16),FREEWAT
      COMMON HOLDCAP
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      COMMON IDATE(372),ISNOW,ITABLE
      COMMON KOUNT
      COMMON LASTUSD,LINES
      COMMON NEXTACT
      COMMON OBSWEQV
      COMMON PACKTEM,PARTICE,PASTINT,PLOTOBS,PLOTWE,PRECIP,PREWEQV
      COMMON RADIN,RADLWN,RADSWN,REFLECT
      COMMON SIMTEM1(3),SIMTEM2,SIMTEM3,SNOMELT,SOBSEQV(372),
     1       SPRECIP(372),SPREQV(372),SUBTITL(8)
      COMMON TCOEFF,TEMPMAX,TEMPMIN,THRSHLD,TITLE(8),TOTPREC
      COMMON USEMEAN
      COMMON XMAX
      INTEGER ACTDATE
      INTEGER DATE,DATES,DREADY
      INTEGER FOOTNOT
      INTEGER PASTINT,PLOTOBS,PLOTWE
      INTEGER SUBTITL
      INTEGER TITLE
      INTEGER USEMEAN
      COMMON/CONVERT/FIVE9TH,THIRTY2
C-----START THE ENERGY BALANCE AND SNOWMELT AT ZERO FOR THIS INTERVAL,
C-----  BUT ACCUMULATE THE PRECIPITATION
      ISNOW = 0
      ENGBAL = 0.0
      SNOMELT = 0.0
      TOTPREC = TOTPREC + PRECIP
C-----IF A SNOWPACK ALREADY EXISTS, GO FIND THE EFFECT OF THIS INTERVAL
C-----  ON THE SNOWPACK
      IF(PREWEQV) 10,10,40
C-----SINCE THERE IS NO SNOWPACK, CHECK TO SEE IF THIS INTERVAL HAS ANY
C-----  PRECIPITATION AND IF SO, SEE IF IT IS ALL SNOW
      IF(PRECIP) 120,120,20
C-----IF THE MINIMUM TEMPERATURE IS BELOW FREEZING, CONSIDER THE
C-----  PRECIPITATION TO BE ALL SNOW
      IF(TEMPMIN.LE.THIRTY2.OR.TEMPMAX.LE.BASTEMF) GO TO 60
C-----SEE IF THE PRECIPITATION IS ALL RAIN OR A MIXTURE ON BARE GROUND
      IF(TEMPMIN - BASTEMF) 90,30,30
C-----IT IS ALL RAIN, DO NOT START BUILDING UP THE SNOWPACK
      SNOMELT = PRECIP
      GO TO 120
C-----A SNOWPACK EXISTS.  IF THERE IS PRECIPITATION, DETERMINE THE TYPE.
C-----  BUT OTHERWISE, JUST GO ON TO COMPUTE THE REFLECTIVITY AND
C-----  RADIATION BALANCE
   10 IF(PRECIP) 110,110,50
C-----THERE IS PRECIPITATION ON AN EXISTING PACK.  IF IT IS NOT ALL
C-----  SNOW, GO SEE IF ANY OF IT WAS SNOW
      IF(TEMPMIN.GT.THIRTY2.AND.TEMPMAX.GT.BASTEMF) GO TO 70
      CALL SNOWED (AMIN1 (AVETEMC,0.0),PRECIP)
      GO TO 110
C-----SEE WHETHER THE PRECIPITATION ON AN EXISTING PACK WAS ALL RAIN OR
C-----  A MIXTURE OF RAIN AND SNOW
   20 IF(TEMPMIN - BASTEMF) 90,80,80
C-----THIS IS A RAIN ON SNOW EVENT.  THE TEMPERATURE FOR COMPUTING THE
C-----  DEPLETION OF THE TOTAL CALORIE DEFICIT IS THE DIFFERENCE OF THE
C-----  AVERAGE TEMPERATURE AND FREEZING (0.0 DEGREES CENTIGRADE)
      CALL RAINED (AVETEMC,PRECIP)
      GO TO 100
C-----THIS IS A MIXTURE OF RAIN AND SNOW EVENT
   30 CALL MIXTURE
C-----IF THE PACK WAS ENTIRELY MELTED, BYPASS COMPUTATION OF THE
C-----  REFLECTIVITY AND THE RADIATION BALANCE
      IF(PREWEQV) 120,120,110
C-----GET THE REFLECTIVITY FOR THIS INTERVAL
   40 CALL GETREF
C-----COMPUTE THE RADIATION BALANCE AND ITS EFFECT ON THE PACK
      CALL RADBAL
      RETURN
C-----THERE IS NO SNOWPACK - REDEFINE THE RADIATION BALANCE TO A
C-----  NEGATIVE VALUE TO ASSURE THE PROPER SELECTION OF THE REFLECTIVITY
C-----  FUNCTION IN SUBROUTINE GETREF WHEN THERE IS A SNOWPACK
   50 CALORIE = -1.0
      RETURN
      END
```

routine CALIN

```
      SUBROUTINE CALIN (CALORIN)
C-----THIS SUBROUTINE COMPUTES THE EFFECTS OF THE CALORIC INPUT ON THE
C-----  SNOWPACK
      COMMON ACTDATE,ACTUAL(21),AVETEMC,AVETEMF
      COMMON BASTEMF
      COMMON CALAIR,CALDEF,CALORIE,CALSNOW,COVDEN
      COMMON DATE,DATES(3),DEN,DENSITY,DREADY
      COMMON ENGBAL
      COMMON FOOTNOT(16),FREEWAT
      COMMON HOLDCAP
      COMMON IDATE(372),ISNOW,ITABLE
      COMMON KOUNT
      COMMON LASTUSD,LINES
      COMMON NEXTACT
      COMMON OBSWEQV
      COMMON PACKTEM,PARTICE,PASTINT,PLOTOBS,PLOTWE,PRECIP,PREWEQV
      COMMON RADIN,RADLWN,RADSWN,REFLECT
      COMMON SIMTEM1(3),SIMTEM2,SIMTEM3,SNOMELT,SOBSEQV(372),
     1       SPRECIP(372),SPREQV(372),SUBTITL(8)
      COMMON TCOEFF,TEMPMAX,TEMPMIN,THRSHLD,TITLE(8),TOTPREC
      COMMON USEMEAN
      COMMON XMAX
      INTEGER ACTDATE
      INTEGER DATE,DATES,DREADY
      INTEGER FOOTNOT
      INTEGER PASTINT,PLOTOBS,PLOTWE
      INTEGER SUBTITL
      INTEGER TITLE
      INTEGER USEMEAN
C-----ADD THESE CALORIES INTO THE ENERGY BALANCE
      ENGBAL = ENGBAL + CALORIN
C-----SEE IF A CALORIE DEFICIT EXISTS IN THE PACK
      COMPARE = CALORIN - CALDEF
      IF(COMPARE) 10,20,30
C-----THERE IS A CALORIE DEFICIT, BUT THE INPUT DID NOT COMPLETELY
C-----  WIPE IT OUT.  ALL OTHER CONDITIONS ARE UNCHANGED
   10 CALDEF = - COMPARE
C-----1.27 = 0.05 * 2.54
      PACKTEM = COMPARE/(PREWEQV*1.27)
      RETURN
C-----THE CALORIE DEFICIT WAS WIPED OUT, BUT ALL OTHER CONDITIONS ARE
C-----  UNCHANGED
   20 CALDEF = 0.0
      PACKTEM = 0.0
      RETURN
C-----ANY DEFICIT WHICH DID EXIST WAS WIPED OUT.  COMPUTE THE POTENTIAL
C-----  MELT FROM THE REMAINING CALORIES (CALORIES/(80.0 * 2.54))
   30 POTMELT = COMPARE/203.2
      CALDEF = 0.0
      PACKTEM = 0.0
C-----IF THE INPUT WAS ENOUGH TO MELT THE WHOLE PACK, CONTRIBUTE THE
C-----  WATER EQUIVALENT TO THE SNOWMELT AND ZERO ALL CONDITIONS
      IF(POTMELT.LT.PARTICE) GO TO 40
      SNOMELT = SNOMELT + PREWEQV
      PREWEQV = 0.0
      PARTICE = 0.0
      FREEWAT = 0.0
      HOLDCAP = 0.0
      RETURN
C-----DEPLETE THE ICE PACK BY THE AMOUNT MELTED AND CONTRIBUTE THAT
C-----  AMOUNT TO THE FREE WATER
   40 PARTICE = PARTICE - POTMELT
      FREEWAT = FREEWAT + POTMELT
C-----COMPUTE THE NEW HOLDING CAPACITY OF THE PACK AND COMPARE IT WITH
C-----  THE FREE WATER TO SEE IF SNOWMELT IS PRODUCED
      HOLDCAP = 0.04 * PARTICE
      COMPARE = FREEWAT - HOLDCAP
      IF(COMPARE.LE.0.0) RETURN
C-----THE SNOWMELT CONTRIBUTED IS IN -COMPARE-.  REDUCE THE FREE WATER
C-----  TO LEAVE A PRIMED PACK AND REDUCE THE PREDICTED WATER EQUIVALENT
      PREWEQV = PREWEQV - COMPARE
      SNOMELT = SNOMELT + COMPARE
      FREEWAT = HOLDCAP
      RETURN
      END
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Subroutine CALOSS

```
      SUBROUTINE CALOSS (CALOUT)
C-----THIS SUBROUTINE COMPUTES THE EFFECTS OF THE CALORIC LOSS ON THE
C-----  SNOWPACK
      COMMON ACTDATE,ACTUAL(21),AVETEMC,AVETEMF
      COMMON BASTEMF
      COMMON CALAIR,CALDEF,CALORIE,CALSNOW,COVDEN
      COMMON DATE,DATES(3),DEN,DENSITY,DREADY
      COMMON ENGBAL
      COMMON FOOTNOT(16),FREEWAT
      COMMON HOLDCAP
      COMMON IDATE(372),ISNOW,ITABLE
      COMMON KOUNT
      COMMON LASTUSD,LINES
      COMMON NEXTACT
      COMMON OBSWEQV
      COMMON PACKTEM,PARTICE,PASTINT,PLOTOBS,PLOTWE,PRECIP,PREWEQV
      COMMON RADIN,RADLWN,RADSWN,REFLECT
      COMMON SIMTEM1(3),SIMTEM2,SIMTEM3,SNOMELT,SOBSEQV(372),
     1       SPRECIP(372),SPREQV(372),SUBTITL(8)
      COMMON TCOEFF,TEMPMAX,TEMPMIN,THRSHLD,TITLE(8),TOTPREC
      COMMON USEMEAN
      COMMON XMAX
      INTEGER ACTDATE
      INTEGER DATE,DATES,DREADY
      INTEGER FOOTNOT
      INTEGER PASTINT,PLOTOBS,PLOTWE
      INTEGER SUBTITL
      INTEGER TITLE
      INTEGER USEMEAN
C-----ADD ALGEBRAICALLY THESE CALORIES INTO THE ENERGY BALANCE
      ENGBAL = ENGBAL + CALOUT
C-----SEE IF THERE IS ANY FREE WATER IN THE PACK.  IF NOT, THE LOSS IS
C-----  JUST CONTRIBUTED TO THE CALORIC DEFICIT OF THE SNOWPACK.
C-----  REMEMBER THAT -CALOUT- IS NEGATIVE
      IF(FREEWAT.GT.0.0) GO TO 10
      CALDEF = CALDEF - CALOUT
      GO TO 50
C-----COMPUTE THE CALORIC LOSS NECESSARY TO FREEZE ALL OF THE FREE WATER
C-----  (FREE WATER * 80.0 * 2.54)
   10 CALNEED = FREEWAT * 203.2
C-----NOW COMPARE THAT NECESSARY LOSS WITH THE ACTUAL LOSS.  IF THEY ARE
C-----  THE SAME, THE FREE WATER IS WIPED OUT BUT NO OTHER CONDITIONS ARE
C-----  ALTERED
      COMPARE = CALOUT + CALNEED
      IF(COMPARE) 20,30,40
C-----THE LOSS WAS MORE THAN ENOUGH TO FREEZE IT.  THE BALANCE CREATES
C-----  AN ENERGY DEFICIT IN THE PACK AND THE FREE WATER IS WIPED OUT
   20 CALDEF = - COMPARE
   30 PARTICE = PARTICE + FREEWAT
      FREEWAT = 0.0
      GO TO 50
C-----ONLY PART OF THE FREE WATER FREZE.  COMPUTE THE BALANCE REMAINING
C-----  BALANCE = EXISTING FREE WATER - AMOUNT FROZEN, WHERE
C-----  AMOUNT FROZEN = CALORIES/(80.0 * 2.54)
   40 FROZEN = - CALOUT/203.2
```

```
      PARTICE = PARTICE + FROZEN
      FREEWAT = FREEWAT + FROZEN
      RETURN
C-----COMPUTE THE NEW PACK TEMPERATURE AND HOLD CAPACITY
   50 PACKTEM = -CALDEF/(PREWEQV*1.27)
      HOLDCAP = 0.04 * PARTICE
      RETURN
      END
```

Subroutine DIFMOD

```
      SUBROUTINE DIFMOD
C-----THIS SUBROUTINE WAS DERIVED FROM PROGRAM SIMTEM, A SNOWPACK
C-----  TEMPERATURE DIFFUSION MODEL DEVELOPED BY LEAF (1970 STUDY PLAN
C-----  FS-RM-1602, NO. 224, RMF+RES).  USING THE AVERAGE SURFACE TEMP
C-----  AND THE GROUND TEMP AS BOUNDARY CONDITIONS, THE NEW AVERAGE
C-----  SNOWPACK TEMPERATURE IS CALCULATED
      COMMON ACTDATE,ACTUAL(21),AVETEMC,AVETEMF
      COMMON BASTEMF
      COMMON CALAIR,CALDEF,CALORIE,CALSNOW,COVDEN
      COMMON DATE,DATES(3),DEN,DENSITY,DREADY
      COMMON ENGBAL
      COMMON FOOTNOT(16),FREEWAT
      COMMON HOLDCAP
      COMMON IDATE(372),ISNOW,ITABLE
      COMMON KOUNT
      COMMON LASTUSD,LINES
      COMMON NEXTACT
      COMMON OBSWEQV
      COMMON PACKTEM,PARTICE,PASTINT,PLOTOBS,PLOTWE,PRECIP,PREWEQV
      COMMON RADIN,RADLWN,RADSWN,REFLECT
      COMMON SIMTEM1(3),SIMTEM2,SIMTEM3,SNOMELT,SOBSEQV(372),
     1       SPRECIP(372),SPREQV(372),SUBTITL(8)
      COMMON TCOEFF,TEMPMAX,TEMPMIN,THRSHLD,TITLE(8),TOTPREC
      COMMON USEMEAN
      COMMON XMAX
      INTEGER ACTDATE
      INTEGER DATE,DATES,DREADY
      INTEGER FOOTNOT
      INTEGER PASTINT,PLOTOBS,PLOTWE
      INTEGER SUBTITL
      INTEGER TITLE
      INTEGER USEMEAN
C-----
C-----DICTIONARY
C
C      CALDM - THE CALORIC INPUT OR LOSS AS DERIVED BY THE DIFFUSION
C                  MODEL
C      CONST1 - THE FIRST CONSTANT IN THE EQUATION FOR THE SIMULATION
C      CONST2 - THE SECOND CONSTANT IN THE EQUATION FOR THE SIMULATION
C      H - THE DISTANCE BETWEEN NODES (CORRESPONDS TO THE -H- IN THE
C                  STUDY PLAN)
C-----
      COMMON/CONVERT/FIVE9TH,THIRTY2
C-----IF THIS IS THE DATE OF THE ACTUAL OR OBSERVED PACK TEMPERATURES,
C-----  BYPASS THE SIMULATION AND USE THE OBSERVED AVERAGE
      IF(DATE - ACTDATE) 10,100,10
C-----IF THE DENSITY WAS NOT SPECIFIED ON THE INPUT CARD, COMPUTE IT AS
C-----  A FUNCTION OF THE WATER EQUIVALENT.  (THE FUNCTION WAS DERIVED
C-----  FROM OBSERVED CONDITIONS ON THE FRASER EXPERIMENTAL FOREST)
   10 IF(DEN) 20,20,30
   20 DENSITY = (EXP((0.0179 * PREWEQV) + 3.02))/100.0
      GO TO 40
   30 DENSITY = DEN
C-----COMPUTE THE DISTANCE BETWEEN THE TWO NODES IN CENTIMETERS
C-----DEPTH = PREWEQV/DENSITY
C-----H = (DEPTH/2)*2.54
   40 H = (PREWEQV/DENSITY) * 1.27
C-----THE THERMAL DIFFUSIVITY IS CALCULATED FROM THE FUNCTION
C-----  KV = 0.01/((2.751 - DENSITY)* 0.48).  MATHEMATICAL STABILITY
C-----  REQUIRES THAT THE VALUE OF THE QUANTITY (INTERVAL IN SECONDS *
C-----  KV/H**2) BE LESS THAN 0.5.  WHEN A 24 HOUR INTERVAL IS USED, THE
C-----  SNOW DEPTH MUST EXCEED 30 INCHES (20 PERCENT DENSITY) TO ACHIEVE
C-----  STABILITY.  IN ORDER TO INSURE STABILITY WITH SOMEWHAT SHALLOWER
C-----  PACKS (ABOUT 18 INCHES), THE DAY IS DIVIDED INTO 2 TIME INTERVALS
C-----  OF 12 HOURS (43200 SECONDS)
C-----CONST1 = (43200 * 0.01/((2.751 - DENSITY) * 0.48))/H**2
      CONST1 = 900.0/((2.751 - DENSITY)*H*H)
C-----THE MINIMUM WATER EQUIVALENT WHICH WILL ACHIEVE STABILITY USING
C-----  THE ABOVE DENSITY FUNCTION IS 4.7 INCHES
      IF(CONST1 - 0.5) 60,50,50
C-----THE MODEL IS UNSTABLE - INDICATE THAT IT IS NOT READY FOR USE NOW.
C-----  (IT MAY BE INITIALIZED AGAIN BY AN OBSERVED PACK TEMPERATURE CARD
C-----  AND STABILITY WILL BE ASCERTAINED FROM THE WATER EQUIVALENT AT
C-----  THAT TIME)
   50 DREADY = 0
      RETURN
C-----GET THE SECOND CONSTANT
   60 CONST2 = 1.0 - CONST1 - CONST1
C-----PERFORM THE SIMULATION IN TWO PARTS (ONE FOR EACH 12 HOUR PERIOD).
C-----  -SIMTEM1- HOLDS THE THREE TEMPERATURES FROM THE PREVIOUS INTERVAL
C-----  THAT ARE NEEDED TO SIMULATE SIMTEM2, THE NODE AT THE CENTER OF
C-----  THE PACK.  SIMULATE THE FIRST 12 HOURS NOW
      SIMTEM2 = (CONST1 * (SIMTEM1(1) + SIMTEM1(3))) + (CONST2 * SIMTEM1
     1(2))
C-----THE AVERAGE SNOWPACK TEMPERATURE IS THE AVERAGE OF THE 2 NODES
C-----  (MIDDLE AND GROUND) IN BOTH INTERVALS.  GROUND TEMPERATURE IS
C-----  CONSTANT, SO START THE AVERAGE NOW
      SIMTEM3 = SIMTEM1(3) + SIMTEM1(3) + SIMTEM2
C-----RESET -SIMTEM1- TO THE TEMPERATURES OF THE INTERVAL JUST SIMULATED
C-----  FOR USE IN THE SECOND 12 HOUR INTERVAL SIMULATION.  THE SURFACE
C-----  AIR TEMPERATURE IS SPLIT INTO A LOW AVERAGE ( (MEAN+MIN)/2 ) AND
C-----  A HIGH AVERAGE ( (MEAN+MAX)/2 ) FOR USE WITH THE TWELVE HOUR
C-----  INTERVALS.  USE THE LOW AVERAGE NOW
      SIMTEM1(1) = AMIN1 (0.0,(((TEMPMIN-THIRTY2)*FIVE9TH)+AV
      SIMTEM1(2) = SIMTEM2
C-----SIMULATE THE SECOND 12 HOURS AND COMPUTE THE AVERAGE SN
C-----  TEMPERATURE
      SIMTEM2 = (CONST1 * (SIMTEM1(1) + SIMTEM1(3))) + (CONST
     1(2))
      SIMTEM3 = (SIMTEM3 + SIMTEM2)/4.0
C-----RESET -SIMTEM1- USING THE HIGH AVERAGE FOR USE ON THE F
C-----  INTERVAL OF THE NEXT DAY
      SIMTEM1(1) = AMIN1 (0.0,(((TEMPMAX-THIRTY2)*FIVE9TH)+AV
      SIMTEM1(2) = SIMTEM2
C-----CHECK TO SEE IF THE GROUND TEMPERATURE SHOULD BE RAISED
      IF(SIMTEM3 + 1.5) 100,80,70
   70 IF(SIMTEM3 + 0.5) 80,90,90
   80 IF(SIMTEM1(3).LT.-0.5) SIMTEM1(3) = -0.5
      RETURN
   90 SIMTEM1(3) = 0.0
  100 RETURN
      END
```

Subroutine GETREF

```
      SUBROUTINE GETREF
C-----GET THE REFLECTIVITY
C-----
C-----DICTIONARY
C
C      REFACUM - A REFLECTIVITY FUNCTION FOR THE SNOWPACK DURI
C                  ACCUMULATION PHASE OF THE SNOWPACK
C      REFMELT - A REFLECTIVITY FUNCTION FOR THE SNOWPACK DURI
C                  MELT PHASE OF THE SNOWPACK
C-----
      COMMON ACTDATE,ACTUAL(21),AVETEMC,AVETEMF
      COMMON BASTEMF
      COMMON CALAIR,CALDEF,CALORIE,CALSNOW,COVDEN
      COMMON DATE,DATES(3),DEN,DENSITY,DREADY
      COMMON ENGBAL
      COMMON FOOTNOT(16),FREEWAT
      COMMON HOLDCAP
      COMMON IDATE(372),ISNOW,ITABLE
      COMMON KOUNT
      COMMON LASTUSD,LINES
      COMMON NEXTACT
      COMMON OBSWEQV
      COMMON PACKTEM,PARTICE,PASTINT,PLOTOBS,PLOTWE,PRECIP,PR
      COMMON RADIN,RADLWN,RADSWN,REFLECT
      COMMON SIMTEM1(3),SIMTEM2,SIMTEM3,SNOMELT,SOBSEQV(372),
     1       SPRECIP(372),SPREQV(372),SUBTITL(8)
      COMMON TCOEFF,TEMPMAX,TEMPMIN,THRSHLD,TITLE(8),TOTPREC
      COMMON USEMEAN
      COMMON XMAX
      INTEGER ACTDATE
      INTEGER DATE,DATES,DREADY
      INTEGER FOOTNOT
      INTEGER PASTINT,PLOTOBS,PLOTWE
      INTEGER SUBTITL
      INTEGER TITLE
      INTEGER USEMEAN
      DIMENSION REFACUM(15),REFMELT(15)
      DATA REFACUM/.80, .77, .75, .72, .70, .69, .68, .67, .6
     1 .64, .63, .62, .61, .60/
      DATA REFMELT/.72, .65, .60, .58, .56, .54, .52, .50, .4
     1 .44, .43, .42, .41, .40/
C-----INCREASE THE INTERVAL COUNTER BY 1 AND SEE IF THERE WAS
      PASTINT = PASTINT + 1
      IF(ISNOW) 10,10,80
C-----USE THE SAME FUNCTION AS LAST TIME
   10 IF(LASTUSD) 20,20,50
C-----ACCUMULATION PHASE - AFTER 15 DAYS, USE THE MELT FUNCTI
C-----  STARTING AT THE FOURTH DAY
   20 IF(PASTINT - 15) 30,30,40
   30 REFLECT = REFACUM(PASTINT)
      RETURN
   40 PASTINT = 4
      LASTUSD = 1
      GO TO 70
C-----MELT FUNCTION - AFTER 15 DAYS, USE A CONSTANT 40 PERCEN
   50 IF(PASTINT - 15) 70,70,60
   60 PASTINT = 15
   70 REFLECT = REFMELT(PASTINT)
      RETURN
C-----THERE IS NEW SNOW - DETERMINE IF THE FUNCTION IS TO BE I
C-----  INITIALIZED
   80 IF(TEMPMAX - THRSHLD) 90,90,10
C-----IT IS, SO SEE WHICH FUNCTION IS TO BE USED
   90 PASTINT = 0
      IF(PACKTEM) 100,110,110
  100 REFLECT = 0.91
      LASTUSD = 0
      RETURN
C-----THE PACK IS ISOTHERMAL, BUT IF THE ENERGY BALANCE FROM T
C-----  PREVIOUS INTERVAL WAS NEGATIVE, USE THE ACCUMULATION PH
C-----  FUNCTION ANYWAY
  110 IF(CALORIE) 100,120,120
  120 REFLECT = 0.81
      LASTUSD = 1
      RETURN
      END
```

Subroutine INITIAL

```
      SUBROUTINE INITIAL
C-----READ THE PARAMETERS AND INITIALIZE THE MELT MODEL
```

```
OMMON ACTDATE,ACTUAL(21),AVETEMC,AVETEMF
OMMON BASTEMF
OMMON CALAIR,CALDEF,CALORIE,CALSNOW,COVDEN
OMMON DATE,DATES(3),DEN,DENSITY,DREADY
OMMON ENGBAL
OMMON FOOTNOT(16),FREEWAT
OMMON HOLDCAP
OMMON IDATE(372),ISNOW,ITABLE
OMMON KOUNT
OMMON LASTUSD,LINES
OMMON NEXTACT
OMMON OBSWEQV
OMMON PACKTEM,PARTICE,PASTINT,PLOTOBS,PLOTWE,PRECIP,PREWEQV
OMMON RADIN,RADLWN,RADSWN,REFLECT
OMMON SIMTEM1(3),SIMTEM2,SIMTEM3,SNOMELT,SOBSEQV(372),
     SPRECIP(372),SPREQV(372),SUBTITL(8)
OMMON TCOEFF,TEMPMAX,TEMPMIN,THRSHLD,TITLE(8),TOTPREC
OMMON USEMEAN
OMMON XMAX
NTEGER ACTDATE
NTEGER DATE,DATES,DREADY
NTEGER FOOTNOT
NTEGER PASTINT,PLOTOBS,PLOTWE
NTEGER SUBTITL
NTEGER TITLE
NTEGER USEMEAN
STABLISH THE STANDARD BASE TEMPERATURE
ASTEMF = 35.0
NITIALIZE THOSE VARIABLES WHICH ARE NOT READ IN OR OTHERWISE
INITIALIZED BEFORE BEING USED
REEWAT = 0.0
OLDCAP = 0.0
UM = 0.0
OTAL = 0.0
MAX = 0.0
READY = 0
SNOW = 0
OUNT = 0
ASTUSD = 0
ASTINT = 0
INES = 999
TART THE RADIATION BALANCE WITH A NEGATIVE VALUE FOR POSSIBLE USE
BY SUBROUTINE GETREF IN DETERMINING WHICH REFLECTIVITY FUNCTION
TO USE
ALORIE = -1.0
EAD THE INSTRUCTION PARAMETERS AND THE CONTROLS ON THE MODEL
EAD (5,910) ITABLE,PLOTWE,PLOTOBS,USEMEAN,TCOEFF,COVDEN,PACKTEM,
PREWEQV,THRSHLD
ORMAT(4I1,1X,5F5.2)
F(EOF(5)) 10,10,20
EAD THE TITLE, SUBTITLE AND FOOTNOTE CARDS
EAD (5,920) TITLE,SUBTITL,FOOTNOT
ORMAT(8A10)
NITIALIZE THE ICE CONTENT AND ACCUMULATED PRECIPITATION
ARTICE = PREWEQV
OTPREC = PREWEQV
ALCULATE THE CALORIE DEFICIT FROM THE PACK TEMPERATURE
ALDEF = - (PACKTEM * 80) * (PREWEQV * 2.54) / 160
ALDEF = - PACKTEM * PREWEQV * 1.27
ETURN
TOP
ND
```

utine LINK

```
UBROUTINE LINK (IRETURN)
HIS SUBROUTINE IS THE INTERFACE BETWEEN THE RADIATION BALANCE
(SUBROUTINE RADBAL) AND THE DIFFUSION MODEL (SUBROUTINE DIFMOD)
OMMON ACTDATE,ACTUAL(21),AVETEMC,AVETEMF
OMMON BASTEMF
OMMON CALAIR,CALDEF,CALORIE,CALSNOW,COVDEN
OMMON DATE,DATES(3),DEN,DENSITY,DREADY
OMMON ENGBAL
OMMON FOOTNOT(16),FREEWAT
OMMON HOLDCAP
OMMON IDATE(372),ISNOW,ITABLE
OMMON KOUNT
OMMON LASTUSD,LINES
OMMON NEXTACT
OMMON OBSWEQV
OMMON PACKTEM,PARTICE,PASTINT,PLOTOBS,PLOTWE,PRECIP,PREWEQV
OMMON RADIN,RADLWN,RADSWN,REFLECT
OMMON SIMTEM1(3),SIMTEM2,SIMTEM3,SNOMELT,SOBSEQV(372),
     SPRECIP(372),SPREQV(372),SUBTITL(8)
OMMON TCOEFF,TEMPMAX,TEMPMIN,THRSHLD,TITLE(8),TOTPREC
OMMON USEMEAN
OMMON XMAX
NTEGER ACTDATE
NTEGER DATE,DATES,DREADY
NTEGER FOOTNOT
NTEGER PASTINT,PLOTOBS,PLOTWE
NTEGER SUBTITL
NTEGER TITLE
NTEGER USEMEAN
OMMON/CONVERT/FIVE9TH,THIRTY2
EE IF THE RADIATION BALANCE IS AN ENERGY LOSS OR GAIN
F(CALORIE) 10,10,80
HERE WAS A LOSS.  IF THIS IS STILL WINTER (NO FREEWATER), JUST
GO AHEAD AND USE THE DIFFUSION MODEL
F(FREEWAT) 20,20,50
SE THE DIFFUSION MODEL TO SIMULATE THE CURRENT AVERAGE SNOWPACK
EMPERATURE
ALL DIFMOD
F(DREADY) 40,40,30
C-----NOW MAKE ANY NECESSARY ADJUSTMENTS IN THE RADIATION BALANCE TO
C-----  CAUSE THE PACK TEMPERATURE TO BE THE SAME AS -SIMTEM3-.  START BY
C-----  GETTING THE DIFFERENCE BETWEEN THE LAST PACK TEMPERATURE AND THIS
C-----  ONE, THEN CONVERT IT TO CALORIES
   30 CALDM = (SIMTEM3 - PACKTEM) * PREWEQV * 1.27
C-----ADJUST THE LONG WAVE PORTION OF THE RADIATION BALANCE BY THE
C-----  DIFFERENCE BETWEEN THE CALORIES DERIVED FROM THE DIFFUSION MODEL
C-----  AND THE ENERGY BALANCE
      RADLWN = RADLWN + (CALDM - CALORIE)
      CALORIE = CALDM
   40 IRETURN = 0
      RETURN
C-----THE LOSS IS USED TO FREEZE PART OR ALL OF THE FREE WATER, BUT IT
C-----  MAY NOT CREATE COLD CONTENT.  IF IT WOULD CREATE COLD CONTENT,
C-----  RE-INITIALIZE THE DIFFUSION MODEL TO 0 AND ADJUST THE ENERGY
C-----  BALANCE ACCORDINGLY
   50 CALL CALOSS (CALORIE)
      IF(FREEWAT - 0.5) 60,60,70
   60 SIMTEM1(1) = AMIN1 (AVETEMC,0.0)
      SIMTEM1(2) = 0.0
      SIMTEM1(3) = 0.0
      DREADY = 1
C-----MAKE ANY NECESSARY ADJUSTMENTS TO THE ENERGY BALANCE TO COMPENSATE
C-----  FOR THE COLD CONTENT THAT WOULD HAVE BEEN GENERATED BY THIS LOSS
C-----  AND ZERO THE COLD CONTENT
      CALORIE = CALORIE + CALDEF
      RADLWN = RADLWN + CALDEF
      PARTICE = PARTICE + FREEWAT
      PREWEQV = PREWEQV + FREEWAT
      FREEWAT = 0.0
      CALDEF = 0.0
      PACKTEM = 0.0
   70 IRETURN = 1
      RETURN
C-----THERE IS CALORIC INPUT TO THE PACK.  CHECK TO SEE IF CONDITIONS
C-----  INDICATE THAT THE DIFFUSION MODEL SHOULD BE TURNED OFF AND THE
C-----  ENERGY BALANCE USED FOR SPRINGTIME SIMULATION.  CONSIDER FIRST
C-----  ANY COLD CONTENT (INCLUDING THAT OF THE PREVIOUS DAY AND ANY
C-----  CREATED BY A SNOW EVENT ON THIS DAY).  IF THERE IS COLD CONTENT,
C-----  CHECK THE AVERAGE AIR TEMPERATURE AND THE SNOWPACK TEMPERATURE
C-----  FROM THE PREVOUS DAY FOR ARBITRARILY CHOSEN SPRINGTIME CONDITIONS
C-----  AND IF ALL ARE NOT SATISFIED, GO AHEAD AND USE THE DIFFUSION
C-----  MODEL
   80 IF(CALDEF) 170,170,90
   90 IF(AVETEMC.LE.0.0.OR.PACKTEM.LE.-0.7) GO TO 20
C-----SINCE SPRINGTIME CONITIONS PREVAIL, RECOMPUTE THE BACK RADIATION
C-----  AND THE NET RADIATION BALANCE (REMEMBER, IF THERE IS SNOW, THE
C-----  LONGWAVE IS ASSUMED TO BE ZERO, SO THERE WOULD BE NO NEED TO MAKE
C-----  ANY ADJUSTMENTS)
      IF(ISNOW) 100,100,140
  100 USE = (TEMPMIN - THIRTY2) * FIVE9TH
      IF(USE.GT.0.0) USE = 0.0
      CALSNOW = 1.17E-7 * ((USE + 273.16) ** 4)
      IF(PRECIP) 110,110,120
  110 RADLWN = ((1.0 - COVDEN) * (10.757 * CALAIR) - CALSNOW)) + (COVDEN
     1 * (CALAIR - CALSNOW))
      GO TO 130
  120 RADLWN = CALAIR - CALSNOW
  130 CALORIE = RADSWN + RADLWN
C-----RE-INITIALIZE THE DIFFUSION MODEL TO THESE CONDITIONS (BUT IF THE
C-----  INPUT IS MORE THAN ENOUGH TO WIPE OUT THE CALORIE DEFICIT, JUST
C-----  LET IT BRING THE PACK TO ISOTHERMAL.  IN THIS WAY, TWO CONSECU-
C-----  TIVE DAYS OF INPUT ARE REQUIRED TO GENERATE FREE WATER)
  140 ACTDATE = DATE
      COMPARE = CALORIE - CALDEF
      IF(COMPARE) 160,150,150
C-----INITIALIZE THE DIFFUSION MODEL TO ISOTHERMAL CONDITIONS
  150 SIMTEM1(1) = 0.0
      SIMTEM1(2) = 0.0
      SIMTEM1(3) = 0.0
      SIMTEM3 = 0.0
      GO TO 20
C-----REDEFINE THE SURFACE TEMPERATURE AND COMPUTE THE NEW AVERAGE PACK
C-----  TEMPERATURE.  THEN COMPUTE THE MIDDLE NODE AS A FUNCTION OF THAT
C-----  AVERAGE, THE SURFACE TEMPERATURE AND THE GROUND TEMPERATURE
C-----  (WHICH REMAINED UNCHANGED)
  160 SIMTEM1(1) = AMIN1 (0.0,AVETEMC)
      SIMTEM3 = COMPARE/(PREWEQV * 1.27)
      SIMTEM1(2) = (3.0 * SIMTEM3) - SIMTEM1(1) - SIMTEM1(3)
      SIMTEM1(3) = 0.0
      GO TO 20
C-----THERE IS INPUT TO THE PACK AND THE PACK IS ALREADY ISOTHERMAL.  IF
C-----  THIS ENERGY WILL CREATE AT LEAST 0.05 INCH (ARBITRARY AMOUNT) OF
C-----  FREE WATER, TURN THE DIFFUSION MODEL OFF AND LET THE ENERGY
C-----  BALANCE TAKE ITS COURSE
  170 IF(FREEWAT + (CALORIE/203.2) - 0.05) 150,180,180
  180 DREADY = 0
      IRETURN = 0
      RETURN
      END
```

Subroutine MIXTURE

```
      SUBROUTINE MIXTURE
C----THIS SUBROUTINE CONTROLS THE COMPUTATIONS FOR A PRECIPITATION
C-----  EVENT THAT IS A MIXTURE OF SNOW AND RAIN
C-----
C-----DICTIONARY
C-----
C     AMTSNOW - THE AMOUNT OF PRECIPITATION OCCURRING AS SNOW (INCHES)
C     TFORAIN - THE TEMPERATURE FOR COMPUTING THE DEPLETION OF THE TOTAL
C                  CALORIE DEFICIT CAUSED BY THE RAIN (DEGREES C)
C     TFORSNO - THE TEMPERATURE FOR COMPUTING THE CONTRIBUTION OF THE
C                  SNOW TO THE TOTAL CALORIE DEFICIT (DEGREES C)
```

```
C-----
      COMMON ACTDATE,ACTUAL(21),AVETEMC,AVETEMF
      COMMON BASTEMF
      COMMON CALAIR,CALDEF,CALORIE,CALSNOW,COVDEN
      COMMON DATE,DATES(3),DEN,DENSITY,DREADY
      COMMON ENGBAL
      COMMON FOOTNOT(16),FREEWAT
      COMMON HOLDCAP
      COMMON IDATE(372),ISNOW,ITABLE
      COMMON KOUNT
      COMMON LASTUSD,LINES
      COMMON NEXTACT
      COMMON OBSWEQV
      COMMON PACKTEM,PARTICE,PASTINT,PLOTOBS,PLOTWE,PRECIP,PREWEQV
      COMMON RADIN,RADLWN,RADSWN,REFLECT
      COMMON SIMTEM1(3),SIMTEM2,SIMTEM3,SNOMELT,SOBSEQV(372),
     1       SPRECIP(372),SPREQV(372),SUBTITL(8)
      COMMON TCOEFF,TEMPMAX,TEMPMIN,THRSHLD,TITLE(8),TOTPREC
      COMMON USEMEAN
      COMMON XMAX
      INTEGER ACTDATE
      INTEGER DATE,DATES,DREADY
      INTEGER FOOTNOT
      INTEGER PASTINT,PLOTOBS,PLOTWE
      INTEGER SUBTITL
      INTEGER TITLE
      INTEGER USEMEAN
      COMMON/CONVERT/FIVE9TH,THIRTY2
C-----COMPUTE THE AMOUNT OF PRECIPITATION OCCURRING AS SNOW BY
C----- AMOUNT SNOW = P * (1.0 - B/A), WHERE
C----- P = PRECIPITATION IN INCHES
C----- B = DAILY MAXIMUM TEMPERATURE - BASE TEMPERATURE (DEGREES F)
C----- A = DAILY MAXIMUM TEMPERATURE - MINIMUM TEMPERATURE (DEGREES F)
      B = TEMPMAX - BASTEMF
      A = TEMPMAX - TEMPMIN
      AMTSNOW = PRECIP * (1.0 - (B/A))
C-----NOW COMPUTE THE AVERAGE TEMPERATURES (DEGREES C) WHICH PRODUCE
C----- SNOW AND RAIN
      TFORSNO = (((TEMPMIN + BASTEMF) * 0.5) - THIRTY2) * FIVE9TH
      TFORAIN = (((TEMPMAX + BASTEMF) * 0.5) - THIRTY2) * FIVE9TH
C-----COMPUTE THE EFFECT OF THE SNOW ON THE SNOWPACK
      CALL SNOWED (TFORSNO,AMTSNOW)
C-----COMPUTE THE EFFECT OF THAT PORTION OF THE PRECIPITATION OCCURRING
C----- AS RAIN ON THE SNOWPACK
      CALL RAINED (TFORAIN,PRECIP-AMTSNOW)
      RETURN
      END
```

Subroutine PLOTTER

```
      SUBROUTINE PLOTTER
C-----THIS SUBROUTINE CONTROLS THE PLOTTING OF THE MODEL OUTPUT
      COMMON ACTDATE,ACTUAL(21),AVETEMC,AVETEMF
      COMMON BASTEMF
      COMMON CALAIR,CALDEF,CALORIE,CALSNOW,COVDEN
      COMMON DATE,DATES(3),DEN,DENSITY,DREADY
      COMMON ENGBAL
      COMMON FOOTNOT(16),FREEWAT
      COMMON HOLDCAP
      COMMON IDATE(372),ISNOW,ITABLE
      COMMON KOUNT
      COMMON LASTUSD,LINES
      COMMON NEXTACT
      COMMON OBSWEQV
      COMMON PACKTEM,PARTICE,PASTINT,PLOTOBS,PLOTWE,PRECIP,PREWEQV
      COMMON RADIN,RADLWN,RADSWN,REFLECT
      COMMON SIMTEM1(3),SIMTEM2,SIMTEM3,SNOMELT,SOBSEQV(372),
     1       SPRECIP(372),SPREQV(372),SUBTITL(8)
      COMMON TCOEFF,TEMPMAX,TEMPMIN,THRSHLD,TITLE(8),TOTPREC
      COMMON USEMEAN
      COMMON XMAX
      INTEGER ACTDATE
      INTEGER DATE,DATES,DREADY
      INTEGER FOOTNOT
      INTEGER PASTINT,PLOTOBS,PLOTWE
      INTEGER SUBTITL
      INTEGER TITLE
      INTEGER USEMEAN
      DIMENSION LEGEND(8)
      DATA LEGEND/ 8OH1 = PREDICTED WATER EQUIVALENT, 2 = OBSERVED WATER
     1 EQUIVALENT, 3 = PRECIPITATION/
C-----TURN OFF THE AUTOMATIC PAGE EJECT
      WRITE (6,910)
  910 FORMAT(*Q*)
C-----INITIALIZE THE PLOT ROUTINE
      CALL TSPLOT (3,0,0,0,0,0,0,XMAX,0.0,IDATE(1),7,-1)
C-----PLOT ONE LINE FOR EACH INTERVAL
      DO 10 I = 1,KOUNT
   10 CALL TSPLOT (3,SPREQV(I),SOBSEQV(I),SPRECIP(I),0.0,0.0,0.0,XMAX,
     1 0.0,IDATE(I),7,1)
C-----WRITE THE TITLE AND OTHER IDENTIFYING INFORMATION
      WRITE (6,920) TITLE,SUBTITL,TCOEFF,COVDEN,LEGEND,FOOTNOT
  920 FORMAT(1H026X8A10/27X8A10/* TRANSMISIVITY COEFFICIENT =*F4.2,74X
     1 *COVER DENSITY =*F4.2/1H0,19X*PLOT LEGEND -- *8A10//1H013A10/1X
     2 3A10)
C-----TURN THE AUTOMATIC PAGE EJECT BACK ON
      WRITE (6,930)
  930 FORMAT(*R*)
      RETURN
      END
```

Subroutine RADBAL

```
      SUBROUTINE RADBAL
C-----THIS SUBROUTINE COMPUTES THE RADIATION BALANCE AND TRANS
C----- CONTROL TO THE DIFFUSION MODEL IF IT IS NEEDED
C-----
C-----DICTIONARY
C-----
C      SNOCAN - THE LONGWAVE RADIATION BALANCE BETWEEN THE SNOW
C               CANOPY
C      SNOSKY - THE LONGWAVE RADIATION BALANCE BETWEEN THE SNOW
C               SKY
      COMMON ACTDATE,ACTUAL(21),AVETEMC,AVETEMF
      COMMON BASTEMF
      COMMON CALAIR,CALDEF,CALORIE,CALSNOW,COVDEN
      COMMON DATE,DATES(3),DEN,DENSITY,DREADY
      COMMON ENGBAL
      COMMON FOOTNOT(16),FREEWAT
      COMMON HOLDCAP
      COMMON IDATE(372),ISNOW,ITABLE
      COMMON KOUNT
      COMMON LASTUSD,LINES
      COMMON NEXTACT
      COMMON OBSWEQV
      COMMON PACKTEM,PARTICE,PASTINT,PLOTOBS,PLOTWE,PRECIP,PREV
      COMMON RADIN,RADLWN,RADSWN,REFLECT
      COMMON SIMTEM1(3),SIMTEM2,SIMTEM3,SNOMELT,SOBSEQV(372),
     1       SPRECIP(372),SPREQV(372),SUBTITL(8)
      COMMON TCOEFF,TEMPMAX,TEMPMIN,THRSHLD,TITLE(8),TOTPREC
      COMMON USEMEAN
      COMMON XMAX
      INTEGER ACTDATE
      INTEGER DATE,DATES,DREADY
      INTEGER FOOTNOT
      INTEGER PASTINT,PLOTOBS,PLOTWE
      INTEGER SUBTITL
      INTEGER TITLE
      INTEGER USEMEAN
      COMMON/CONVERT/FIVE9TH,THIRTY2
C-----COMPUTE THE CALORIC INPUT FROM NET SHORT WAVE RADIATION AI
C----- FUNCTION OF THE REFLECTIVITY
      RADSWN = RADIN * (1.0 - REFLECT) * TCOEFF
C-----IF THE PRECIP WAS SNOW, THE NET LONG WAVE RADIATION BALAN
C----- ASSUMED TO BE ZERO
      IF(ISNOW) 20,20,10
   10 RADLWN = 0.0
      GO TO 50
C-----TO COMPUTE THE LONG WAVE RADIATION COMPONENTS, CONVERT TH
C----- AND SNOW TEMPERATURES TO POTENTIAL CALORIES BY THE STEFA
C----- BLOTZMANN FUNCTION, CALORIES = S * (T ** 4), WHERE
C----- S = 1.17E-7 CAL/((CM**2)(DEGREES KELVIN)**4), AND
C----- T = ABSOLUTE TEMPERATURE (DEGREES KELVIN)
   20 CALAIR = 1.17E-7 * ((AVETEMC + 273.16) ** 4)
      USE = AVETEMC
C-----IF THE SNOWPACK IS ISOTHERMAL, USE THE MINIMUM TEMPERATURI
C----- COMPUTING THE BACK RADIATION
      IF(CALDEF.EQ.0.0) USE = (TEMPMIN - THIRTY2) * FIVE9TH
C-----UNDER NO CIRCUMSTANCES MAY THE TEMPERATURE FOR COMPUTING
C----- RADIATION BE GREATER THAN ZERO
      IF(USE.GT.0.0) USE = 0.0
      CALSNOW = 1.17E-7 * ((USE + 273.16) ** 4)
C-----COMPUTE THE LONG WAVE RADIATION COMPONENTS AS A FUNCTION C
C----- FIRST, DETERMINE WHETHER THE SKIES ARE CLEAR OR CLOUDY
      IF(PRECIP) 30,30,40
C-----WITH CLEAR SKIES, THE DOWNWARD LONGWAVE RADIATION COEFFIC
C----- .757 (RUNOFF FROM SNOWMELT, EM1110-2-1406, US ARMY CORPS
C----- ENGINEERS, 1960, PAGE 7)
   30 SNOSKY = (1.0 - COVDEN) * ((0.757 * CALAIR) - CALSNOW)
C-----THE DOWNWARD LONGWAVE RADIATION COEFFICIENT IS 1.0 BENEATH
C----- FOREST CANOPY (OR BENEATH CLOUDY SKIES)
      SNOCAN = COVDEN * (CALAIR - CALSNOW)
      RADLWN = SNOCAN + SNOSKY
      GO TO 50
C-----WITH CLOUDY SKIES, WHEN THE DOWNWARD LONGWAVE RADIATION CO
C----- CIENT IS 1.0 INSTEAD OF .757, THE ABOVE THREE EQUATIONS M
C----- REDUCED ALGEBRAICALLY TO THE FOLLOWING SINGLE EQUATION
   40 RADLWN = CALAIR - CALSNOW
C-----COMPUTE THE CALORIC INPUT OR LOSS FROM THE NET EFFECT OF S
C----- WAVE AND LONG WAVE RADIATION
   50 CALORIE = RADSWN + RADLWN
C-----THE SNOWPACK TEMPERATURE DIFFUSION MODEL (LEAF, 1970, STUD
C----- FS-RM-1602, NO. 224.  ROCKY MOUNTAIN FOREST AND RANGE EXP
C----- INCORPORATED TO CONTROL THE SNOWPACK TEMPERATURE AND COLD
C----- DURING NON-ISOTHERMAL CONDITIONS.  SEE NOW IF THE DIFFUSI
C----- HAS BEEN INITIALIZED.  IF SO, GO THROUGH THE LINKING ROUT
C----- WHICH INTERFACES THE DIFFUSION MODEL WITH THE RADIATION B
      IF(DREADY) 60,70,60
   60 CALL LINK (IRETURN)
      IF(IRETURN) 70,70,90
   70 IF(CALORIE) 80,90,100
   80 CALL CALOSS (CALORIE)
   90 RETURN
  100 CALL CALIN (CALORIE)
      RETURN
      END
```

Subroutine RAINED

```
      SUBROUTINE RAINED (TFORAIN,AMTRAIN)
C-----THIS SUBROUTINE COMPUTES THE EFFECT OF RAIN ON SNOW
C-----
```

```
CTIONARY
TRAIN - THE AMOUNT OF PRECIPITATION OCCURRING AS RAIN (INCHES)
LRAIN - THE DEPLETION OF THE TOTAL CALORIE DEFICIT BY THIS RAIN
        (CALORIES)
DRAIN - THE TEMPERATURE FOR COMPUTING THE DEPLETION OF THE TOTAL
        CALORIE DEFICIT CAUSED BY THIS RAIN (DEGREES C)

MMON ACTDATE,ACTUAL(21),AVETEMC,AVETEMF
MMON BASTEMF
MMON CALAIR,CALDEF,CALORIE,CALSNOW,COVDEN
MMON DATE,DATES(3),DEN,DENSITY,DREADY
MMON ENGBAL
MMON FOOTNOT(16),FREEWAT
MMON HOLDCAP
MMON IDATE(372),ISNOW,ITABLE
MMON KOUNT
MMON LASTUSD,LINES
MMON NEXTACT
MMON OBSWEQV
MMON PACKTEM,PARTICE,PASTINT,PLOTOBS,PLOTWE,PRECIP,PREWEQV
MMON RADIN,RADLWN,RADSWN,REFLECT
MMON SIMTEM1(3),SIMTEM2,SIMTEM3,SNOMELT,SOBSEQV(372),
    SPRECIP(372),SPREQV(372),SUBTITL(8)
MMON TCOEFF,TEMPMAX,TEMPMIN,THRSHLD,TITLE(8),TOTPREC
MMON USEMEAN
MMON XMAX
TEGER ACTDATE
TEGER DATE,DATES,DREADY
TEGER FOOTNOT
TEGER PASTINT,PLOTOBS,PLOTWE
TEGER SUBTITL
TEGER TITLE
TEGER USEMEAN
 THIS AMOUNT OF PRECIPITATION TO THE PREDICTED WATER EQUIVALENT
WEQV = PREWEQV + AMTRAIN
 IF THERE IS A CALORIE DEFICIT IN THE PACK
CALDEF.LE.0.0) GO TO 50
PUTE THE AMOUNT OF RAIN AT THIS TEMPERATURE THAT IS NEEDED TO
PE OUT THE DEFICIT AND COMPARE IT WITH THE ACTUAL AMOUNT
NEED = CALDEF/((80.0 + TFORAIN) * 2.54)
PARE = AMTRAIN - AMTNEED
COMPARE) 20,10,40
RE WAS JUST ENOUGH TO WIPE OUT THE DEFICIT
DEF = 0.0
KTEM = 0.0
TO 30
RE WAS NOT ENOUGH TO WIPE IT OUT COMPLETELY.  JUST DEPLETE
E DEFICIT
DEF = CALDEF - ((80.0 + TFORAIN) * AMTRAIN * 2.54)
KTEM = -CALDEF/(PREWEQV*1.27)
 ALL THE RAIN TO THE PACK AS ICE AND GET THE NEW HOLDING
APACITY
TICE = PARTICE + AMTRAIN
DCAP = 0.04 * PARTICE
URN
RE WAS MORE THAN ENOUGH TO WIPE OUT THE DEFICIT.  ADD THE
OZEN PART TO THE ICE AND GET THE NEW HOLDING CAPACITY
DEF = 0.0
KTEM = 0.0
TICE = PARTICE + AMTNEED
DCAP = 0.04 * PARTICE
 AMOUNT OF RAIN NOT FROZEN IS FREE WATER AND CONTRIBUTES
LORIC INPUT TO THE PACK
EWAT = COMPARE
L CALIN (TFORAIN * COMPARE * 2.54)
URN
 OF THE RAIN IS ADDED TO THE FREE WATER AND CONTRIBUTES CALORIC
PUT TO THE PACK
EWAT = FREEWAT + AMTRAIN
L CALIN (TFORAIN * AMTRAIN * 2.54)
URN
```

tine RDPACK

```
ROUTINE RDPACK
S SUBROUTINE READS THE ACTUAL OR OBSERVED SNOWPACK TEMPERATURE
RD AND INITIALIZES THE DIFFUSION MODEL (SUBROUTINE DIFMOD).  IT
 CALLED WHENEVER COL 70 OF AN INPUT CARD IS NOT BLANK OR ZERO
MMON ACTDATE,ACTUAL(21),AVETEMC,AVETEMF
MMON BASTEMF
MMON CALAIR,CALDEF,CALORIE,CALSNOW,COVDEN
MMON DATE,DATES(3),DEN,DENSITY,DREADY
MMON ENGBAL
MMON FOOTNOT(16),FREEWAT
MMON HOLDCAP
MMON IDATE(372),ISNOW,ITABLE
MMON KOUNT
MMON LASTUSD,LINES
MMON NEXTACT
MMON OBSWEQV
MMON PACKTEM,PARTICE,PASTINT,PLOTOBS,PLOTWE,PRECIP,PREWEQV
MMON RADIN,RADLWN,RADSWN,REFLECT
MMON SIMTEM1(3),SIMTEM2,SIMTEM3,SNOMELT,SOBSEQV(372),
    SPRECIP(372),SPREQV(372),SUBTITL(8)
MMON TCOEFF,TEMPMAX,TEMPMIN,THRSHLD,TITLE(8),TOTPREC
MMON USEMEAN
MMON XMAX
EGER ACTDATE
EGER DATE,DATES,DREADY
EGER FOOTNOT
EGER PASTINT,PLOTOBS,PLOTWE
EGER SUBTITL
EGER TITLE
      INTEGER USEMEAN
      READ (5,910) I,ACTDATE,ACTUAL
  910 FORMAT(A10,1X16,21F3.1)
C-----BE SURE THIS IS AN OBSERVED PACK TEMPERATURE CARD AND THAT THE
C------ DATE IS THE SAME AS THE CARD JUST READ BY SUBROUTINE READER.  IF
C------ NOT, ABORT THE JOB
      IF(I.EQ.10HOBS PACK T) GO TO 20
   10 PRINT 920,DATE,NEXTACT
  920 FORMAT(*1THE INPUT CARD DATED*I7,* INDICATED THAT AN OBSERVED PACK
     1 TEMPERATURE CARD WAS NEXT (COL 70 CONTAINED A*I2,*.* /*BUT EITHE
     2R COLUMNS 1 - 10 OF THE NEXT CARD DO NOT CONTAIN -OBS PACK T-  OR
     3HE DATES ARE NOT THE SAME*)
      CALL SYSTEM (999,12H-JOB ABORTED)
   20 IF(DATE - ACTDATE) 10,30,10
C-----GET THE ACTUAL AVERAGE SNOWPACK TEMPERATURE (THE TEMPERATURES READ
C------ IN ARE ALL POSITIVE - THE NEGATIVES WILL BE INSERTED BY THIS
C------ SUBROUTINE)
   30 DUMMY1 = 1.0
      DUMMY2 = ACTUAL(20)
      DO 60 I = 1,19
C-----WATCH FOR BLANKS TO PREVENT AVERAGING ZEROES (A BLANK IS READ AS A
C------ NEGATIVE ZERO, WHICH MAY BE DETECTED BY THE FOLLOWING TWO TESTS)
      IF(ACTUAL(I)) 50,40,50
   40 IF(SIGN(1.0,ACTUAL(I))) 70,70,50
   50 DUMMY1 = DUMMY1 + 1.0
   60 DUMMY2 = DUMMY2 + ACTUAL(I)
C-----COMPUTE THE AVERAGE
   70 SIMTEM3 = - DUMMY2/DUMMY1
C-----FILL IN -SIMTEM1- WITH THE OBSERVED TEMPERATURES.  START WITH THE
C------ AVERAGE AIR TEMPERATURE
      SIMTEM1(1) = AMIN1 (AVETEMC,0.0)
C-----GROUND TEMPERATURE
      SIMTEM1(3) = - ACTUAL(20)
C-----FIND THE MEDIAN DEPTH OF THE PACK FROM THE WATER EQUIVALENT
      WEQV = PREWEQV + PRECIP
C-----IF THE DENSITY WAS NOT SPECIFIED ON THE INPUT CARD, COMPUTE IT A
C------ A FUNCTION OF THE WATER EQUIVALENT.  (THE FUNCTION WAS DERIVED
C------ FROM 1969 OBSERVED CONDITIONS ON THE FRASER EXPERIMENTAL FOREST)
      IF(DEN) 90,90,80
   80 DENSITY = DEN
      GO TO 100
   90 DENSITY = (EXP((10.0179 * WEQV) + 3.02))/100.0
C-----DEPTH = WEQV/DENSITY
C-----MEDIAN = DEPTH/2
  100 DUMMY1 = WEQV/(DENSITY + DENSITY)
C-----INTERPOLATE BETWEEN THE ACTUAL TEMPERATURES ON EITHER SIDE OF THIS
C------ DEPTH TO OBTAIN THE TEMPERATURE.  (THE SUBSCRIPT OF THE TEMP
C------ ABOVE IT IS FOUND BY TRUNCATING THE QUOTIENT OF THIS DEPTH
C------ DIVIDED BY THE DISTANCE BETWEEN MEASUREMENTS.  THE INTERPOLATION
C------ IS LINEAR)
      SUBSCRP = DUMMY1/ACTUAL(21)
      I = SUBSCRP
      TRUNCAT = I
      SIMTEM1(2) = - ACTUAL(I) - ((ACTUAL(I) - ACTUAL(I+1)) * (TRUNCAT -
     1 SUBSCRP))
C-----INDICATE THAT THE DIFFUSION MODEL HAS BEEN INITIALIZED AND IS
C------ READY FOR USE
      DREADY = 1
      RETURN
      END
```

Subroutine READER

```
      SUBROUTINE READER (IEND)
C-----THIS SUBROUTINE READS A DATA CARD AND COMPUTES THE AVERAGE
C------ TEMPERATURES
      COMMON ACTDATE,ACTUAL(21),AVETEMC,AVETEMF
      COMMON BASTEMF
      COMMON CALAIR,CALDEF,CALORIE,CALSNOW,COVDEN
      COMMON DATE,DATES(3),DEN,DENSITY,DREADY
      COMMON ENGBAL
      COMMON FOOTNOT(16),FREEWAT
      COMMON HOLDCAP
      COMMON IDATE(372),ISNOW,ITABLE
      COMMON KOUNT
      COMMON LASTUSD,LINES
      COMMON NEXTACT
      COMMON OBSWEQV
      COMMON PACKTEM,PARTICE,PASTINT,PLOTOBS,PLOTWE,PRECIP,PREWEQV
      COMMON RADIN,RADLWN,RADSWN,REFLECT
      COMMON SIMTEM1(3),SIMTEM2,SIMTEM3,SNOMELT,SOBSEQV(372),
     1       SPRECIP(372),SPREQV(372),SUBTITL(8)
      COMMON TCOEFF,TEMPMAX,TEMPMIN,THRSHLD,TITLE(8),TOTPREC
      COMMON USEMEAN
      COMMON XMAX
      INTEGER ACTDATE
      INTEGER DATE,DATES,DREADY
      INTEGER FOOTNOT
      INTEGER PASTINT,PLOTOBS,PLOTWE
      INTEGER SUBTITL
      INTEGER TITLE
      INTEGER USEMEAN
      COMMON/CONVERT/FIVE9TH,THIRTY2
C-----READ A CARD AND CHECK FOR THE END OF FILE
      READ (5,900) DATES,RADIN,TEMPMAX,TEMPMIN,OBSWEQV,PRECIP,DEN,
     1 NEXTACT
  900 FORMAT(3I2,F4.0,7X,2F4.1,14X3F5.2,15X11)
      IF(EOF(5)) 20,20,10
   10 IEND = 1
      RETURN
   20 IEND = 0
      DATE = DATES(1)*10000 + DATES(2)*100 + DATES(3)
      IF(DATE) 70,70,30
C-----COMPUTE THE MEAN TEMPERATURE IN FAHRENHEIT, THEN CONVERT IT T
```

```
C----- CENTIGRADE
   30 AVETEMF = (TEMPMAX + TEMPMIN) * 0.5
      AVETEMC = (AVETEMF - THIRTY2) * FIVE9TH
      IF(USEMEAN) 50,50,40
   40 TEMPMAX = AVETEMF
      TEMPMIN = AVETEMF
C-----SEE IF THE NEXT CARD IS AN ACTUAL PACK TEMPERATURE CARD
   50 IF(NEXTACT) 70,70,60
   60 CALL RDPACK
   70 RETURN
      END
```

Subroutine SNOWED

```
      SUBROUTINE SNOWED (TFORSNO,AMTSNOW)
C-----THIS SUBROUTINE COMPUTES THE EFFECTS OF A SNOW EVENT ON THE
C-----  SNOWPACK
C-----
C-----DICTIONARY
C-----
C     AMTSNOW - THE AMOUNT OF PRECIPITATION OCCURRING AS SNOW (INCHES)
C     CALSNOW - THE CONTRIBUTION OF THIS SNOW TO THE TOTAL CALORIE
C                 DEFICIT (CALORIES)
C     TFORSNO - THE TEMPERATURE FOR COMPUTING THE CONTRIBUTION OF THIS
C                 SNOW TO THE TOTAL CALORIE DEFICIT (DEGREES C)
C-----
      COMMON ACTDATE,ACTUAL(21),AVETEMC,AVETEMF
      COMMON BASTEMF
      COMMON CALAIR,CALDEF,CALORIE,CALSNOW,COVDEN
      COMMON DATE,DATES(3),DEN,DENSITY,DREADY
      COMMON ENGBAL
      COMMON FOOTNOT(16),FREEWAT
      COMMON HOLDCAP
      COMMON IDATE(372),ISNOW,ITABLE
      COMMON KOUNT
      COMMON LASTUSD,LINES
      COMMON NEXTACT
      COMMON OBSWEQV
      COMMON PACKTEM,PARTICE,PASTINT,PLOTOBS,PLOTWE,PRECIP,PREWEQV
      COMMON RADIN,RADLWN,RADSWN,REFLECT
      COMMON SIMTEM1(3),SIMTEM2,SIMTEM3,SNOMELT,SOBSEQV(372),
     1       SPRECIP(372),SPREQV(372),SUBTITL(8)
      COMMON TCOEFF,TEMPMAX,TEMPMIN,THRSHLD,TITLE(8),TOTPREC
      COMMON USEMEAN
      COMMON XMAX
      INTEGER ACTDATE
      INTEGER DATE,DATES,DREADY
      INTEGER FOOTNOT
      INTEGER PASTINT,PLOTOBS,PLOTWE
      INTEGER SUBTITL
      INTEGER TITLE
      INTEGER USEMEAN
      ISNOW = 1
C-----ADD THIS AMOUNT OF PRECIPITATION TO THE PREDICTED WATER EQUIVALENT
C-----  AND GET THE NEW HOLDING CAPACITY
      PREWEQV = PREWEQV + AMTSNOW
      PARTICE = PARTICE + AMTSNOW
      HOLDCAP = 0.04 * PARTICE
C-----THE SNOW FALLING WHEN THE TEMPERATURE IS BETWEEN 35 AND 32 DEGREES
C-----  DOES NOT ALTER THE CALORIC DEFICIT
      IF(TFORSNO.GE.0.0) RETURN
C-----COMPUTE THE CALORIE DEFICIT FOR THIS SNOW BY THE EQUATION
C-----  CALORIE DEFICIT = S(I)*DELTA T*P, WHERE
C-----  S(I) = SPECIFIC HEAT OF ICE (.5 CAL/CM/DEGREES C),
C-----  DELTA T = CHANGE IN TEMPERATURE WITH RESPECT TO FREEZING (0.0
C-----    DEGREES CENTIGRADE), AND
C-----  P = PRECIPITATION IN CM (CONVERSION FACTOR = 2.54 CM/IN).
C-----  THEREFORE, CALORIE DEFICIT = 0.5 * (TFORSNO) * (AMTSNOW * 2.54)
      CALL CALOSS (TFORSNO * AMTSNOW * 1.27)
      RETURN
      END
```

Subroutine STORE

```
      SUBROUTINE STORE
C-----STORE THE INFORMATION NEEDED FOR THE PLOT
      COMMON ACTDATE,ACTUAL(21),AVETEMC,AVETEMF
      COMMON BASTEMF
      COMMON CALAIR,CALDEF,CALORIE,CALSNOW,COVDEN
      COMMON DATE,DATES(3),DEN,DENSITY,DREADY
      COMMON ENGBAL
      COMMON FOOTNOT(16),FREEWAT
      COMMON HOLDCAP
      COMMON IDATE(372),ISNOW,ITABLE
      COMMON KOUNT
      COMMON LASTUSD,LINES
      COMMON NEXTACT
      COMMON OBSWEQV
      COMMON PACKTEM,PARTICE,PASTINT,PLOTOBS,PLOTWE,PRECIP,PREWEQV
      COMMON RADIN,RADLWN,RADSWN,REFLECT
      COMMON SIMTEM1(3),SIMTEM2,SIMTEM3,SNOMELT,SOBSEQV(372),
     1       SPRECIP(372),SPREQV(372),SUBTITL(8)
      COMMON TCOEFF,TEMPMAX,TEMPMIN,THRSHLD,TITLE(8),TOTPREC
      COMMON USEMEAN
      COMMON XMAX
      INTEGER ACTDATE
      INTEGER DATE,DATES,DREADY
      INTEGER FOOTNOT
      INTEGER PASTINT,PLOTOBS,PLOTWE
      INTEGER SUBTITL
      INTEGER TITLE
      INTEGER USEMEAN
C-----KEEP TRACK OF THE LARGEST VALUE FOR SCALING THE PLOT
      XMAX = AMAX1 (XMAX,OBSWEQV,PREWEQV)
C-----INCREASE THE COUNTER
      KOUNT = KOUNT + 1
      IDATE(KOUNT) = DATE
      SPRECIP(KOUNT) = PRECIP
      SPREQV(KOUNT) = PREWEQV
      IF(PLOTOBS) 10,10,20
C-----BY STORING A NUMBER OUTSIDE THE LIMITS OF THE PLOT, IT
C-----  IGNORED
   10 SOBSEQV(KOUNT) = -1.0
      RETURN
C-----THE OBSERVED WATER EQUIVALENT IS TO BE PLOTTED
   20 SOBSEQV(KOUNT) = OBSWEQV
      RETURN
      END
```

Subroutine TSPLOT

```
      SUBROUTINE TSPLOT(MX,X1,X2,X3,X4,X5,X6,XMAX,XMIN,IT,INT
C-----THIS ROUTINE DOES THE ACTUAL PLOTTING
C. HWANG, A.C. HOGGATT   1 JULY, 1962
C     ARGUMENTS
C    MX=NUMBER OF VARIABLES TO BE PLOTTED, LESS THAN OR EQUAL
C  X1=VALUE ATTACHED TO FIRST VARIABLE. PLOTTING SYMBOL WILL
C  X2=VALUE ATTCHED TO SECOND VARIABLE. PLOTTING SYMBOL WILL
C  X3
C  .
C  .
C  X6 AND SO ON FOR XN
C  XMAX=UPPER END OF ORDINATE SCALE
C  XMIN=LOWER END OF ORDINATE SCALE
C  IT =ABCISSA VALUE. (I.E., T, FOR XT)
C  INT=ABCISSA LABELLING INTERVAL. (I.E., EVERY ICHTH LINE OF
C  WILL BE LABELLED WITH VALUE OF IDY ON HORIZONTAL AXIS)
C  INIT  =INITIALIZING PARAMETER, USED AS FOLLOWS.
C              INIT   =1, GRAPH WILL COMPUTE AND PRINT ORDINAT
C  AND PRINT FIRST LINE OF GRAPH. SUBSEQUENT CALL WILL PLOT A
C  A LINE OF GRAPH ONLY.
C           INIT  =-1 USED TO READY SUBROUTINE FOR PLOTTING NE
C  SUBROUTINE DOES NO PLOTTING OR PRINTING WITH THIS SETTING
C       IF THE VALUE OF SCALING PARAMETERS XMIN AND/OR XMAX DI
C       THE PREVIOUSLY GIVEN ONES WITHOUT RESETTING OF INIT,
C       WILL RESET SCALE ACCORDING TO NEW XMIN AND/OR XMAX AND
C       NEW ORDINATE POINT VALUES TO AGREE WITH SCALING OF PLO
C    INTERNAL VARIABLES
C  CHARS CONTAINS BCD CHARACTERS USED AS PLOTTING SYMBOL.
C  PLOT HOLDS THE HOLLERITH IMAGE FOR ONE LINE OF PLOT.
C  XN. SCALAR ARGUMENTS ARE STORED IN THIS LINEAR ARRAY.
C  DELTA IS A SCALING PARAMETER, EQUAL TO THE RANGE DIVIDED B
C       IS RECOMPUTED WHEN NEW SCALE IS INDICATED (WHEN INIT
C       XMAX OR XMIN VALUE DIFFERING FROM PREVIOUS VALUE IS GI
C  PASMIN, PASMAX, ARE FOR REMEMBERING PREVIOUS VALUE OF XMIN
      DIMENSION CHARS(8), PLOT(111), ORDPT(6), XN(6)
      EQUIVALENCE(ORDPT(6),PLOT(6))
      DATA  CHARS(1)/1H1/, CHARS(2)/1H2/, CHARS(3)/1H3/, CHAR
     *CHARS(5)/1H5/, CHARS(6)/1H6/, CHARS(7)/1H /, CHARS(8)/1
      DATA NCALLS/0/,NDY/0/
      IF(INIT)1000,1000,9001
CALL WAS TO INITIALIZE ONLY....
 1000 NDY=0
      NCALLS=0
      GO TO 701
COMMENCE BY PROTECTING THE INDEX MX
 9001 M=MAXO(MX,1)
      M=MINO(M,6)
CONJURE PLOTTING CHARACTERS
    3 XN(1)=X1
      XN(2)=X2
      XN(3)=X3
      XN(4)=X4
      XN(5)=X5
      XN(6)=X6
      IF(NDY) 15,15,28
   28 IF(PASMAX-XMAX) 45,40,45
   40  IF(PASMIN-XMIN) 45,80,45
   15 NDY=1
COMPUTE AND PRINT ORDINATE POINTS, SCALE.
   45 AN=(XMAX-XMIN)*.2
      ORDPT(1)=XMIN
      NCALLS = 0
      DO 17 I=2,6
   17 ORDPT(I)=ORDPT(I-1)+AN
      WRITE (6,100) (ORDPT(N),N=1,6)
      DO 705 N=1,2
      WRITE (6,101)
  705 CONTINUE
  101 FORMAT(    9X1H.,5(21X1H.))
      WRITE (6,800)
  800 FORMAT(    9X111(1H.))
  100 FORMAT(1H1,4(E10.3,12X),E10.3,11X,E10.3)
      DELTA=(XMAX-XMIN)/110.
CLEAR PRINTER LINE.
   80 DO 99 K=2,111
        PLOT(K)=CHARS(7)
   99 CONTINUE
      PLOT(1)=CHARS(8)
CAUSE X TO BE PUT ON THE INTERVAL (1,111).
   20 DO 34 N=1,M
        LOC=1.5+(XN(N)-XMIN)/DELTA
CHECK FOR X WITHIN THE INTERVAL (XMIN,XMAX),
      IF(LOC) 34,34,811
  811 IF(111-LOC) 34,814,814
CHARACTERS FOR PRINTING NOW GET DROPPED INTO PLACE.
  814 PLOT(LOC)=CHARS(N)
```

```
NTINUE
UTPUT FORMAT.
ALLS=NCALLS+1
(MOD(NCALLS,INT)) 815,2004,815
T ONE LINE OF PLOT.
ITE (6,700) IT,(PLOT(K),K=1,111)
 TO 702
RMAT(1H    I6,2H..111A1)
ITE (6,600) (PLOT(K),K=1,111)
RMAT(9H          111A1)
SMAX=XMAX
SMIN=XMIN
OMPLETED.
TURN
 END
```

tine WRITER

```
BROUTINE WRITER (CODE)
IS SUBROUTINE KEEPS TRACK OF THE PRINTING DETAILS
MMON ACTDATE,ACTUAL(21),AVETEMC,AVETEMF
MMON BASTEMF
MMON CALAIR,CALDEF,CALORIE,CALSNOW,COVDEN
MMON DATE,DATES(3),DEN,DENSITY,DREADY
MMON ENGBAL
MMON FOOTNOT(16),FREEWAT
MMON HOLDCAP
MMON IDATE(372),ISNOW,ITABLE
MMON KOUNT
MMON LASTUSD,LINES
MMON NEXTACT
MMON OBSWEQV
MMON PACKTEM,PARTICE,PASTINT,PLOTOBS,PLOTWE,PRECIP,PREWEQV
MMON RADIN,RADLWN,RADSWN,REFLECT
MMON SIMTEM1(3),SIMTEM2,SIMTEM3,SNOMELT,SOBSEQV(372),
     1       SPRECIP(372),SPREQV(372),SUBTITL(8)
      COMMON TCOEFF,TEMPMAX,TEMPMIN,THRSHLD,TITLE(8),TOTPREC
      COMMON USEMEAN
      COMMON XMAX
      INTEGER ACTDATE
      INTEGER DATE,DATES,DREADY
      INTEGER FOOTNOT
      INTEGER PASTINT,PLOTOBS,PLOTWE
      INTEGER SUBTITL
      INTEGER TITLE
      INTEGER USEMEAN
C-----CHECK THE LINE COUNTER
      IF(LINES - 48) 40,10,10
C-----SEE IF THIS IS STARTING A NEW STATION - IF SO, BYPASS THE FOOTNOTE
   10 IF(LINES - 999) 20,30,30
C-----WRITE THE FOOTNOTE
   20 WRITE (6,910) FOOTNOT
  910 FORMAT(1H0132A10/1X3A10)
C-----HEADINGS
   30 WRITE (6,920) TITLE,SUBTITL
  920 FORMAT(1H1150X*SNOWMELT RUNOFF SIMULATION MODEL*/27X8A10/27X8A10)
      WRITE (6,930) TCOEFF,COVDEN
  930 FORMAT(* TRANSMISIVITY COEFFICIENT =*F4.2,74X*COVER DENSITY =*F7.2
     1)
      WRITE (6,940)
  940 FORMAT(*0*32X*TEMPERATURE (F)   PRECIP (IN)        JET RAD (CAL)
     1ENERGY    SNOWPACK  PREDICTED*/
     223X*DATE       MAX   MIN   AVE    DAY  ACCUM        SHORT     LONG  B
     3AL (CAL)  TEMP (C)  W.E. (IN)*/)
      LINES = 0
   40 WRITE (6,950) DATES,TEMPMAX,TEMPMIN,AVETEMF,PRECIP,TOTPREC,RADSWN,
     1 RADLWN,ENGBAL,PACKTEM,PREWEQV
  950 FORMAT(1H0,20X,I2,2I3,1X3F6.1,2F7.2,3X3F8.1,6XF5.1,5XF6.2)
      LINES = LINES + 2
      RETURN
      END
111       35   40 -450  634 6000
```

Sample Input

```
        1         2         3         4         5         6         7         8
12345678901234567890123456789012345678901234567890123456789012345678901234567890

                    FRASER EXPERIMENTAL FOREST, COLORADO
                     DEADHORSE CREEK, LOWER SOUTH SLOPE
ELEVATION 9800 FT.                                ASPECT SSE, SLOPE 30 PERCENT
 12569 171         310  90                  -0   61                          1
OBS PACK T 012569 45 45 45 45 45 45 45 45 45 45                        10 60
 12669 180         400 190                  -0    5
 12769 189         360 170                  -0   39
 12869 198         280  30                  -0    4
 12969 207         230 -80                  -0    3
 13069 417         210-180                  -0    0
 13169 423         200-140                  -0    0
 20169 234         190-160                  -0    9
 20269 243          60-110                  -0   13
 20369 441         220-230                  -0    0
 20469 447         360-170                  -0    0
 20569 453         350 -60                  -0    0
 20669 279         300  10                  -0    6
 20769 465         250  50                  -0    0
 20869 468         290 -90                  -0    0
 20969 471         370-120                  -0    0
 21069 294         370 -80                  -0    2
 21169 478         410  20                  -0    0
 21269 481         390  30                  -0    0
 21369 300         410  50                  -0    6
 21469 488         360 160                  -0    0
 21569 304         370 -40                  -0    5
 21669 306         360 120                  -0   21
 21769 308         310 -40                  -0    3
 21869 501         400-110                  -0    0
 21969 312         430  10                  -0   27
 22069 314         250 120                  -0   26
 22169 310         270 -10                  -0    9
 22269 509         310 -90                  -0    0
 22369 510         330 -90                  -0    0
 22469 510         360 -10                  -0    0
 22569 511         440  30                  -0    0
 22669 291         470  60                  -0   13
 22769 513         260 -70                  -0    0
 22869 514         420 -80                  -0    0
 30169 279         410 -90                  -0   18                          1
OBS PACK T 030169 31 31 31 31 31 31 31 31                              10 60
 30269 275         380 -90                  -0    2
 30369 516         370 -90                  -0    0
 30469 517         380  20                  -0    0
 30569 264         240 -90                  -0   10
 30669 260         320 -80                  -0   16
 30769 519         200 -90                  -0    0
 30869 522         200-190                  -0    0
 30969 525         210-100                  -0    0
 31069 528         330-210                  -0    0
 31169 530         280-130                  -0    0
 31269 263         270-200                  -0    3
 31369 536         210-140                  -0    0
 31469 539         370-200                  -0    0
 31569 541         420-170                  -0    0
 31669 544         480-150                  -0    0
 31769 547         490  20                  -0    0
 31869 550         470 120                  -0    0
 31969 272         290 130                  -0   31
 32069 555         400 -80                  -0    0
 32169 558         500 -40                  -0    0
 32269 567         490 140                  -0    0
 32369 300         290  60                  -0    3
 32469 312         290  70                  -0    7
 32569 325         190  50                  -0    6
 32669 601         360  50                  -0    0
 32769 610         550 130                  -0    0
 32869 619         550 250                  -0    0
 32969 628         550 240                  -0    0
 33069 636         600 270                  -0    0
 33169 562         630 320                  -0    0
 40169 196         340 300                1060   36                          1
OBS PACK T 040169 01 01 01 01 01 01                                    00 60
 40269 562         560 220                   0    0
 40369 559         580 300                  -0    9
 40469 526         440 260                  -0    0
 40569 685         600 260                  -0    0
 40669 631         560 330                  -0    0
 40769 481         380 180                   0    0
 40869 356         480 190                  -0    0
 40969 669         500 180                 750    0
 41069 645         510 260                   0    0
 41169 481         520 280                  -0    0
 41269 156         370 290                  -0   23
 41369 481         370 270                   0    0
 41469 515         450 260                  -0    0
 41569 384         480 170                 930   60
 41669 180         440 190                  -0    9
 41769 601         450 200                  -0    0
 41869 540         510 210                  -0    6
 41969 718         540 260                  -0    0
 42069 722         570 210                  -0    0
 42169 704         630 310                  -0    0
 42269 576         600 360                 510    0
 42369 612         620 250                  -0   41
 42469 725         620 300                  -0    0
 42569 562         330 150                   0    0
 42669 466         320 130                   0   11
 42769 618         360 140                  -0    0
 42869 673         540 170                  -0    0
 42969 633         520 290                 200    0
 43069 706         530 300                   0    0
 50169 629         610 300                   0    0
 50269 711         680 330                   0    0
 50369 578         630 320                   0    0
 50469 551         460 320                   0    0
 50569 259         450 320                   0    0
 50669 546         380 320                  -0  120
 50769 304         360 320                  -0   64
 50869 600         500 180                  -0    0
 50969 812         600 220                  -0    0
 51069 789         590 300                   0    0
 51169 735         630 340                  -0    0
 51269 635         580 340                  -0    0
 51369 578         620 360                  -0    0
 51469 586         610 320                   0    0
 51569 419         460 320                   0   13
 51669 388         390 310                   0   74
 51769 766         620 300                   0    0
 51869 689         610 380                   0    0
 51969 504         700 390                   0    0
 52069 738         700 420                   6    0
 52169 658         680 360                   0   17
 52269 567         650 340                  -0   17
 52369 530         640 370                   0    0
 52469 711         730 350                  -0    0
 52569 718         760 400                  -0    0
 52669 802         790 440                  -0    0
 52769 618         810 480                   0    0
 52869 686         760 420                   0    0
 52969 646         750 400                   0    0
 53069 726         740 420                   0    0
 53169 667         410 300                   0    0
 60169 691         500 260                   0    0
 60269 653         620 360                   0    0
 60369 643         570 340                   0    0
 60469 691         680 440                   0    0
 60569 614         730 460                   0    0
 60669 384         640 360                   0   19
 60769 346         580 380                   0   44
 60869 595         660 380                   0    1
 60969 634         670 360                   0    0
 61069 566         670 340                   0    0
 61169 288         400 320                   0    0
 61269 403         460 320                   0    0
 61369 490         470 310                   0    0
 61469 403         470 320                   0   14
 61569 307         450 340                   0    0
 61669 486         500 340                   0   13
 61769 221         460 370                   0   54
 61869 422         490 380                   0    0
 61969 595         600 350                   0    0
```

```
 42069 634          640 140                    -0
 42169 662          650 310                    -0
 42269 480          530 370                     0
 42369 365          520 420                    17
 42469 394          520 350                    76
 42569 374          390 330                    21
 42669 451          380 320                    39
 42769 806          640 310                    -0
 42869 816          720 330                    -0
 42969 826          690 320                    -0
 43069 758          693 310                    -0
```

```
      1         2         3         4         5         6         7         8
12345678901234567890123456789012345678901234567890123456789012345678901234567890

111    25   55 -480  843 3200
                FRASER EXPERIMENTAL FOREST, COLORADO
                 DEADHORSE CREEK, UPPER NORTH SLOPE
ELEVATION 10530 FT.
                                                ASPECT NE, SLOPE 35 PERCENT
 12569  59          200 110                   -0   77                  1       009
OBS PACK T 012569 48 48 48 48 48 48 48 48 48 48                                10 60
 12669  63          290 210                   -0    6                            009
 12769  67          250 190                   -0   49                            009
 12869  71          170  50                   -0    5                            009
 12969  75          120 -60                   -0    4                            009
 13069 149          100-160                   -0    0                            009
 13169 153           90-120                   -0    0                            009
 20169  88           80-140                   -0   11                            009
 20269  92          -50 -90                   -0   16                            009
 20369 165          110-210                   -0    0                            009
 20469 169          250-150                   -0    0                            009
 20569 173          240 -40                   -0    0                            009
 20669 108          190  30                   -0    8                            009
 20769 181          140  70                   -0    0                            009
 20869 185          180 -70                   -0    0                            009
 20969 189          260-100                   -0    0                            009
 21069 120          260 -60                   -0    3                            009
 21169 198          300  40                   -0    0                            009
 21269 202          280  50                   -0    0                            009
 21369 128          300  70                   -0    8                            009
 21469 210          250 180                   -0    0                            009
 21569 133          260 -20                   -0    6                            009
 21669 136          250 140                   -0   27                            009
 21769 138          200 -20                   -0    4                            009
 21869 227          290 -90                   -0    0                            009
 21969 143          320  30                   -0   34                            009
 22069 146          140 140                   -0   33                            009
 22169 146          160  10                   -0   11                            009
 22269 242          200 -70                   -0    0                            009
 22369 245          220 -70                   -0    0                            009
 22469 249          250  10                   -0    0                            009
 22569 252          330  50                   -0    0                            009
 22669 144          360  80                   -0   16                            009
 22769 258          150 -50                   -0    0                            009
 22869 262          310 -60                   -0    0                            009
 30169 142          300 -70                   -0   23                  1       009
OBS PACK T 030169 35 35 35 35 35 35 35 35                                      10 60
 30269 142          270 -70                   -0    3                            009
 30369 271          260 -70                   -0    0                            009
 30469 274          270  40                   -0    0                            009
 30569 141          130 -70                   -0   13                            009
 30669 140          210 -60                   -0   20                            009
 30769 284           90 -70                   -0    0                            009
 30869 289           90-170                   -0    0                            009
 30969 294          100 -80                   -0    0                            009
 31069 299          220-190                   -0    0                            009
 31169 303          170-110                   -0    0                            009
 31269 152          160-180                   -0    4                            009
 31369 313          100-120                   -0    0                            009
 31469 318          260-180                   -0    0                            009
 31569 323          310-150                   -0    0                            009
 31669 328          370-130                   -0    0                            009
 31769 332          380  40                   -0    0                            009
 31869 337          360 140                   -0    0                            009
 31969 169          180 150                   -0   39                            009
 32069 347          290 -60                   -0    0                            009
 32169 352          390 -20                   -0    0                            009
 32269 361          380 160                   -0    0                            009
 32369 194          180  80                   -0    4                            009
 32469 205          180  90                   -0    3                            009
 32569 215           80  70                   -0    8                            009
 32669 399          250  70                   -0    0                            009
 32769 408          250  80                   -0    0                            009
 32869 418          320 180                   -0    0                            009
 32969 427          330 170                   -0    0                            009
 33069 437          370 220                   -0    0                            009
 33169 429          430 270                   -0    0                            009
 40169 150          310 200                 1340   45  .28                1       009
OBS PACK T 040169 21 24 27 29 30 30 27 16                                      10 60
```

```
 40269 429          390 180                   -0    0                            00
 40369 470          410 220                   -0   11                            00
 40469 402          340 220                   -0    0                            00
 40569 523          380 220                   -0    0                            00
 40669 482          450 290                   -0    0                            00
 40769 367          300 120                   -0   11                            00
 40869 270          320 130                   -0    0                            00
 40969 511          360 180                 1350    0  .32                1       00
OBS PACK T 040969 34 33 38 23 21 19 17                                         10 60
 41069 492          400 230                   -0    0                            00
 41169 367          450 270                   -0    0                            00
 41269 119          340 250                   -0   29                            00
 41369 367          330 230                   -0    0                            00
 41469 393          360 220                   -0    0                            00
 41569 293          400 200                 1410   76  .30                1       00
OBS PACK T 041569 18 18 16 14 13 12 12 11                                      10 60
 41669 138          280 150                   -0   11                            00
 41769 459          320 150                   -0    0                            00
 41869 412          400 160                   -0    0                            00
 41969 549          440 220                   -0    0                            00
 42069 551          470 170                   -0    0                            00
 42164 538          530 300                   -0    0                            00
 42269 440          450 330                 1290    0  .28                1       00
OBS PACK T 042269 01 02 02 04 05 04 04                                         04 60
 42369 467          550 320                   -0   52                            00
 42469 554          520 240                   -0    0                            00
 42569 429          240  90                   -0    0                            00
 42669 356          200  80                   -0   14                            00
 42769 472          270  80                   -0    0                            00
 42869 514          380 150                   -0    0                            00
 42969 483          420 220                 1230    0                            00
 43069 539          470 260                   -0    0                            00
 50169 480          520 280                   -0    0                            00
 50269 543          550 300                   -0    8                            00
 50369 441          510 280                   -0    0                            00
 50469 466          410 300                   -0    0                            00
 50569 219          350 280                   -0    8                            00
 50669 461          320 280                 1170  152                            00
 50769 257          300 240                   -0   81                            00
 50869 507          380 220                   -0    0                            00
 50969 686          420 260                   -0    0                            00
 51069 667          520 300                   -0    0                            00
 51169 621          480 300                   -0    0                            00
 51269 537          490 320                   -0    0                            00
 51369 488          540 300                 1200    0                            00
 51469 496          470 300                   -0    0                            00
 51569 354          440 280                   -0   16                            00
 51669 328          350 260                   -0   96                            00
 51769 647          510 250                   -0    0                            00
 51869 582          500 340                   -0    0                            00
 51969 426          550 340                   -0    0                            00
 52069 624          580 360                 1210    0                            00
 52169 556          530 310                   -0   15                            00
 52269 479          540 310                   -0   13                            00
 52369 448          540 320                   -0   11                            00
 52469 601          540 320                   -0    0                            00
 52569 607          590 370                   -0    0                            00
 52669 678          630 390                   -0    0                            00
 52769 523          670 420                  760    0                            00
 52869 580          660 380                   -0    0                            00
 52969 546          600 390                   -0    0                            00
 53069 614          600 330                   -0    8                            00
 53169 564          430 260                   -0    5                            00
 60169 670          400 220                   -0    6                            00
 60269 632          480 260                   -0   -0                            00
 60369 623          510 320                  380   -0                            00
 60469 670          610 370                   -0   -0                            00
 60569 595          670 440                   -0    4                            00
 60669 372          580 340                   -0   19                            00
 60769 335          440 340                   -0   44                            00
 60869 577          600 340                   -0   10                            00
 60969 614          610 340                   -0   -0                            00
 61069 549          610 320                   -0    5                            00
 61169 279          340 300                   -0   55                            00
 61269 391          400 300                   -0   36                            00
 61369 474          410 290                   -0   22                            00
 61469 391          410 300                   -0   14                            00
 61569 298          390 320                   -0   52                            00
 61669 465          440 320                   -0   19                            00
 61769 214          400 350                   -0   54                            00
 61869 409          430 350                   -0    2                            00
 61969 577          540 330                   -0   -0                            00
 62069 614          580 320                   -0   -0                            00
 62169 642          590 290                   -0   -0                            00
 62269 465          470 350                   -0   -0                            00
 62369 353          460 400                   -0   17                            00
 62469 381          460 330                   -0   76                            00
 62569 363          330 310                   -0   71                            00
 62669 437          320 300                   -0   39                            00
 62769 781          580 290                    0   -0                            00
 62869 790          660 310                   -0   -0                            00
 62969 800          630 300                   -0   -0                            00
 63069 735          630 290                   -0   -0                            00
```

Leaf, Charles F., and Glen E. Brink.
1973. Computer simulation of snowmelt within a Colorado subalpine watershed. USDA For. Serv. Res. Pap. RM-99, 22 p. Rocky Mt. For. and Range Exp. Stn., Fort Collins, Colo.

A dynamic model which simulates snowmelt in Colorado subalpine watersheds for all combinations of aspect, slope, elevation, and forest cover composition and density is described. The model simulates winter snow accumulation, the energy balance, snowpack condition, and resultant melt in time and space. Detailed flow chart descriptions of the various components of the model and a program listing are presented.

Keywords: Computer models, coniferous forests, model studies, simulation analysis, snowmelt, watershed management.

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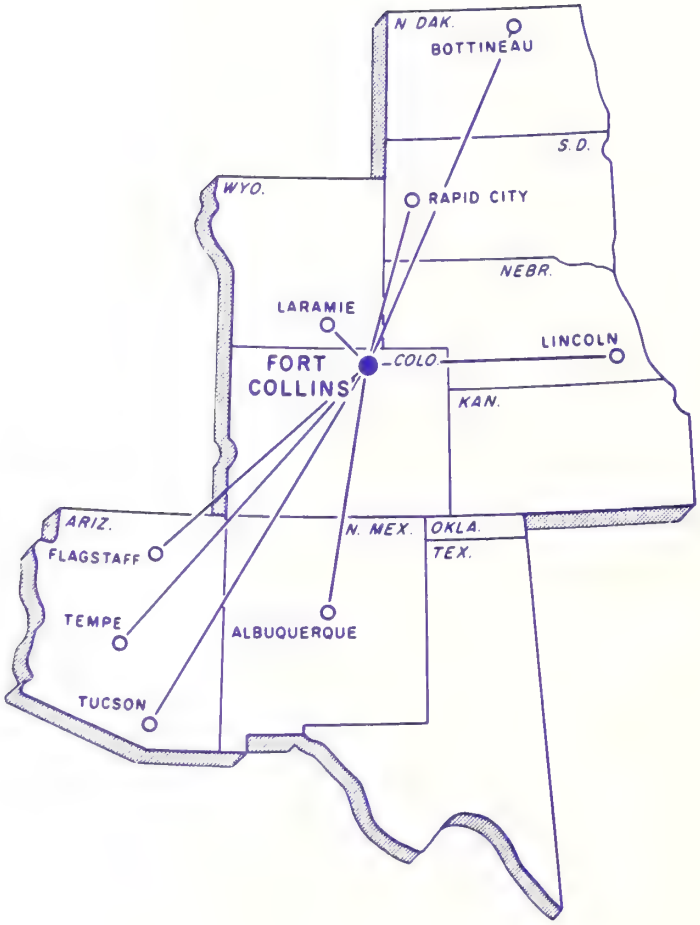
N DAK.
BOTTINEAU
S.D.
WYO.
RAPID CITY
NEBR.
LARAMIE
LINCOLN
FORT
COLLINS
COLO.
KAN.
ARIZ.
N. MEX.
OKLA.
TEX.
FLAGSTAFF
TEMPE
ALBUQUERQUE
TUCSON

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epartment of Agriculture

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WATER YIELD CHARACTERISTICS OF THREE SMALL WATERSHEDS IN THE BLACK HILLS OF SOUTH DAKOTA

by Howard K. Orr and
Tony VanderHeide

Abstract

Three small forested watersheds (217, 89, and 190 acres) on the Vanocker laccolith in the northeastern Black Hills have yielded surface runoff equivalent to 7.12, 7.57, and 6.51 inches, or 25, 27, and 23 percent of average annual precipitation, water years 1964-69, inclusive. The gaging stations are well sealed on bedrock. Base flows are negligible. Hence, the net differences between input precipitation and measured outflow closely approximate yearly evapotranspiration. Data such as these provide for better understanding of the hydrologic behavior of pine-forested watersheds in the interior Black Hills, and thus provide criteria for more enlightened management prescriptions.

Keywords: Water yield, hydrology, evapotranspiration, Black Hills, *Pinus ponderosa*.

USDA Forest Service
Research Paper RM-100

February 1973

Water Yield Characteristics of Three Small Watersheds in the Black Hills of South Dakota

by

Howard K. Orr, Hydrologist
Rocky Mountain Forest and Range Experiment Station[1]

and

Tony VanderHeide, Hydrologist
Black Hills National Forest
Custer, South Dakota

[1]*Research reported here was conducted at Station's Research Work Unit at Rapid City, in cooperation with South Dakota School of Mines and Technology; central headquarters maintained at Fort Collins in cooperation with Colorado State University.*

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The Study Watersheds	1
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Seasonal Distribution	6
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Water Yield Characteristics of Three Small Watersheds in the Black Hills of South Dakota

Howard K. Orr and Tony VanderHeide

In 1961 the Forest Service started a project to gage and study streamflow and related factors on three small watersheds in the northeastern Black Hills. The study is providing the most complete and accurate inventory of water yield above the "zone of water loss" (seepage into sedimentary formations) in any drainage of the Black Hills area. In addition it is expected to provide criteria that will allow a better general understanding of how watersheds function in the interior Black Hills, and assist in the design of water management prescriptions. One of the watersheds is presently being treated to determine if there are significant effects of timber management, as presently practiced in the Black Hills, on water yield and quality.

This report presents information about water yield through water year 1969 in relation to several measured input variables.

The General Setting

Climate in the Black Hills area is of the modified continental type characterized by Johnson (1949) as having "winters comparatively cold and summers comparatively warm; by moderate precipitation, low relative humidity, rapid evaporation, and abundant sunshine; with few, some however notable, exceptions in extremes of heat and cold." Average annual precipitation ranges from a low of about 14 inches on the nearby plains to a maximum of nearly 30 inches in the northern and higher Hills (fig. 1).

Precipitation is of the plains type. Greatest concentrations are in the form of rain in late spring and early summer; amounts decrease steadily through the summer. Smallest amounts, mainly snow, are received in fall and winter.

The Black Hills are the vestigial remains of a domal uplift from which overlying sedimentary formations have been removed by erosion, exposing the crystalline core of Precambrian granite and metamorphosed rock (fig. 2). Upwarped sedimentary formations remain as ridges and valleys encircling the Hills. Recent Tertiary intrusive bodies (laccoliths) occur at scattered locations across the northern Hills. Elevations range from a minimum of 3,200 feet at Rapid City to a maximum of 7,242 feet (m.s.l.) at Harney Peak in the granite area.

Soils range from well-developed podzols to azonal lithosols, and are widely variable.

The Study Watersheds

The study area encompasses three headwater tributaries of Alkali Creek, 5 to 6 miles southwest of Sturgis, on the Vanocker laccolith (fig. 2). The three watersheds, referred to collectively as the Sturgis Watersheds (fig. 3), are: No. 1, 217 acres; No. 2, 89 acres; and No. 3, 190 acres. These headwater tributaries have been a main water source for the Sturgis municipal water supply system for many years.

According to the best available isohyetal map (fig. 1) the study watersheds lie in the 20- to 22-inch precipitation zone. Annual precipitation during the study has averaged considerably above this range, however.

Rock type is hornblende-biotite quartz latite porphyry. Exceptions are a small cap-area of limestone in the vicinity of Veteran Peak, the high point in the area (5,333 feet), and a small area of metamorphosed and highly mineralized sedimentary rock in the vicinity of gaging stations 2 and 3, and for some distance upstream in both drainages. The parent porphyry is a fine-grained, crystalline rock, impervious except for joints and fractures. For the most part, the porphyry weathers slowly in the Black Hills climate. Although soils in the watershed area are relatively shallow (1 to 3 feet) and stony, they generally have well-developed horizons and are classified in the Gray Wooded soils group. Water infiltrates rapidly. Underlying rock is fractured but apparently has small storage capacity. Void space is lacking except for joints and fractures, which decrease in frequency with increasing depth. The combination of steep terrain and shallow, stony soil, underlain by relatively impervious bedrock of low storage capacity,

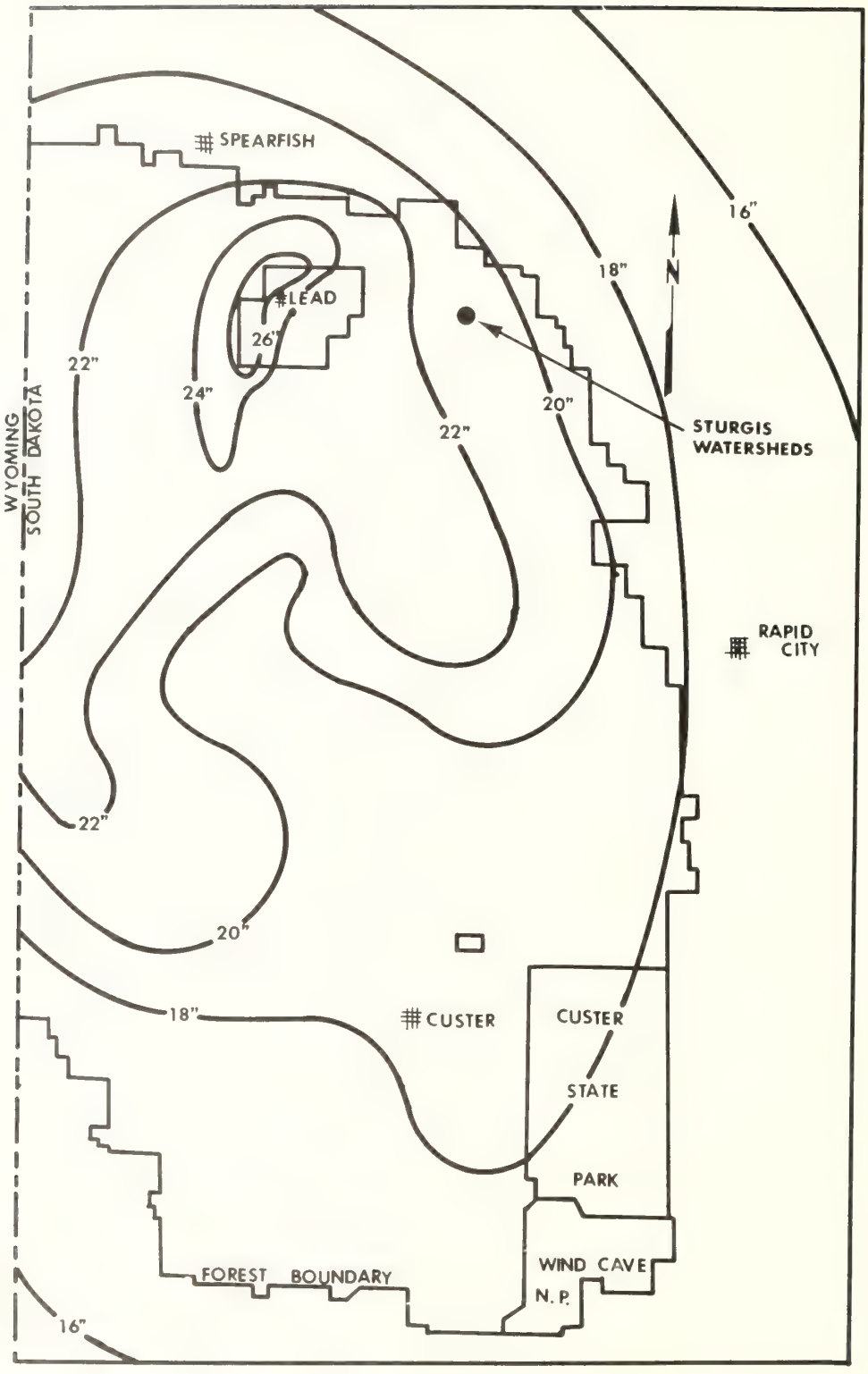
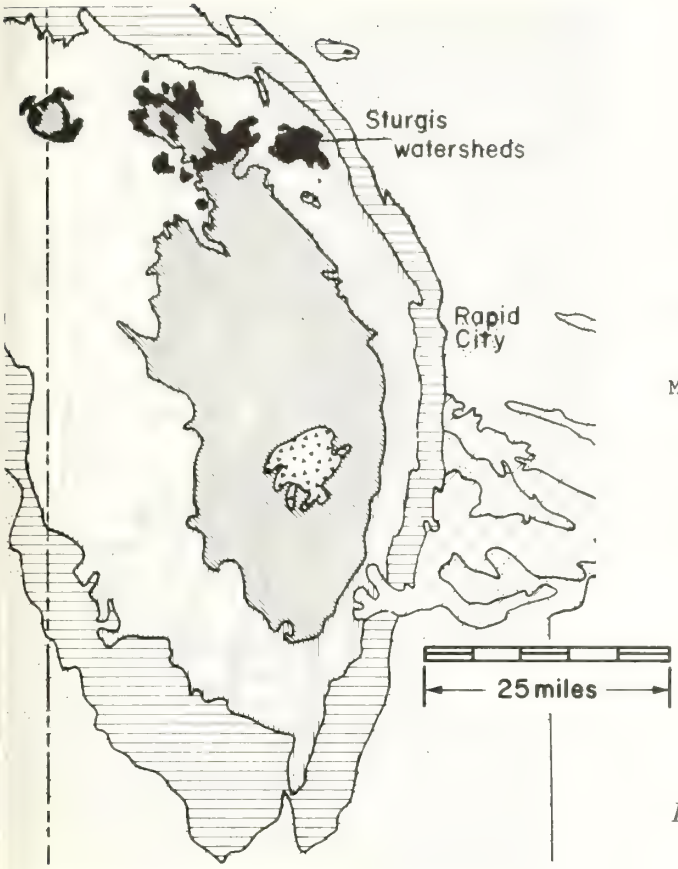


Figure 1.—Isohyetal map of average annual precipitation in the Black Hills area.



LEGEND

Tertiary igneous intrusive rocks

Tertiary sedimentary rocks

Mesozoic rocks from Newcastle Sandstone (Lower Cretaceous) to top of Upper Cretaceous

Mesozoic rocks below Newcastle sandstone (Lower Cretaceous). Includes Spearfish Formation, which is mainly Triassic but partly Permian.

Paleozoic rocks

Precambrian granite

Precambrian metamorphic rocks

Figure 2.—Location of the Sturgis watersheds.

results in quick response to precipitation and rapid drainout to very low base flow.

Ponderosa pine forest dominates all three watersheds (table 1, fig. 4). Included in the forest classification is birch, aspen, ironwood, and bur oak which together occupy 5 percent of total area in watershed 2 and which are also found scattered along the stream channels in all three watersheds. Other than forest acres, the remaining area is rock outcrop or open rockslide where there is practically no vegetation.

The small old-growth sawtimber totals 1,500 or more board feet per acre. Mortality is high but there are enough second-growth seedlings, saplings, and poles present to maintain reasonable timber stocking levels over most of the area. A large proportion of the seedling-saplings occur within the sawtimber stands but some are independent. There are also some small areas of sawtimber with virtually no tree understory.

There has been little use or activity in the area for many years except for a small amount of mountain pine beetle control. The area as a whole is in highly stable hydrologic condition.

Precipitation is gaged in a network of seven stations (fig. 3), the first of which was placed in operation in late fall 1961. Precipitation averages for individual watersheds have been calculated by the Thiessen polygon method of weighting (Foster 1948, p. 153). Automatic recording gages at three of the seven stations provide indices of precipitation intensity, frequency, and duration.

Table 1.--Summary of forest types and areas in the Sturgis watersheds

Item	Unit of measure	Watershed 1	2	3
TOTAL AREA:				
Acres	Number	217	89	190
Forested	Percent	87	97	98
Small sawtimber	Percent	76	90	79
Seedling-sapling understory	Percent	62	58	84
Average basal area	Sq.ft./acre	120	130	166
FORESTED AREA:				
Small sawtimber	Percent	88	93	81
Seedling-sapling understory	Percent	72	60	86
Average basal area	Sq.ft./acre	138	141	170

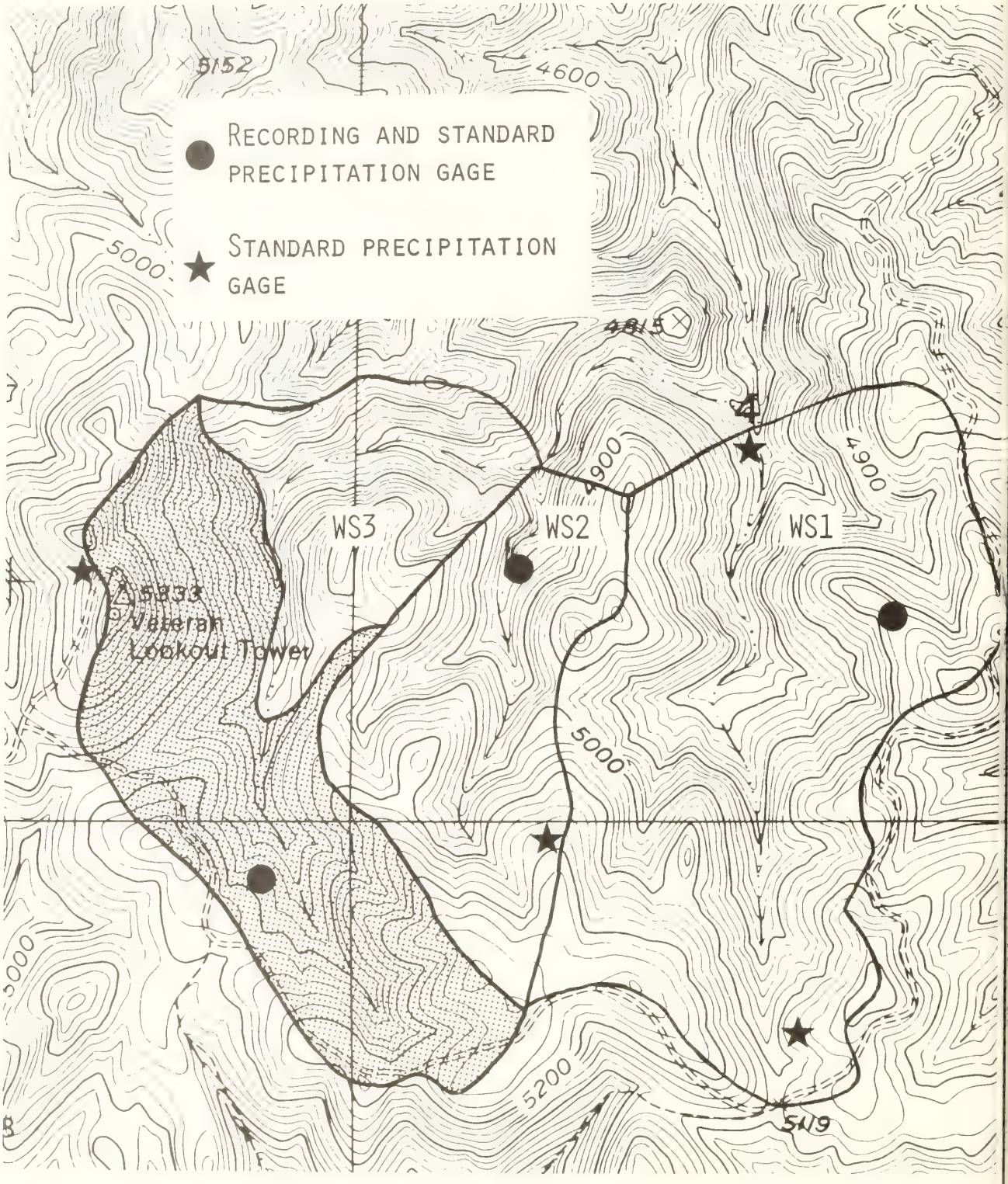


Figure 3.—Topography of the Sturgis watersheds. Shaded portion of watershed 3 is to receive first timber harvest treatment.

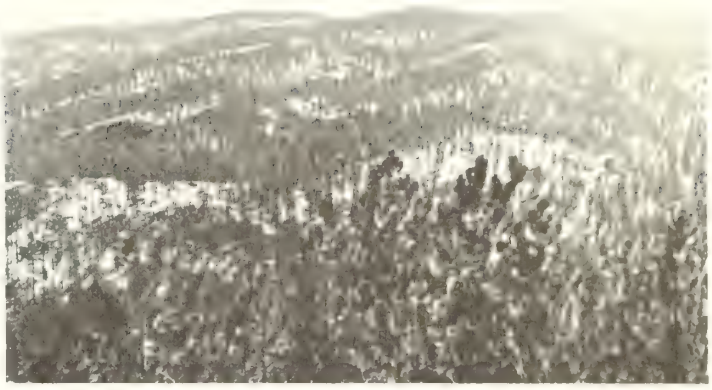


Figure 4.—Looking west to east across Sturgis watersheds from top of Veteran Peak. Forest cover is predominantly ponderosa pine, ranging from sapling size to overmature sawtimber.

The stream gage in watershed 1 was onstructed during the summer of 1962, and the tation was placed in operation December 1, 962. Watersheds 2 and 3 gaging stations were laced in operation in November 1963. The tations are a tandem 120 degree V-notch veir/San Dimas flume arrangement (fig. 5). The V-notch weirs provide the sensitivity necessary or accurate measurement of low flows, and the ectangular flumes the capacity for neasurement of high flows.

Results

Annual Yields

Annual water yields have averaged 25, 27, nd 23 percent of annual precipitation on vatersheds 1, 2, and 3, respectively over a period f 6 water years, 1964 through 1969 (table 2). A water year is defined as October1 through the following September 30. The yearly amounts have ranged from about 27 to 200 percent of average.

Maximum yield did not occur in the year of maximum precipitation on any of the three watersheds, nor did the minimum yields occur in the year of minimum precipitation. These seeming anomalies are related to seasonal distribution of precipitation in relation to evapotranspiration stress. Greater amounts of moisture evaporate and are transpired during periods of high stress, providing moisture is available, and greater proportions of incoming moisture will generally be lost the larger the amount of precipitation.

Watershed 3 has yielded significantly less water than watersheds 2 or 1 (indicated by t-test), not because evapotranspiration stress is greater, but because watershed 3 apparently stores more water in the mantle within easy reach for evapotranspiration.

Figure 5.—Stream gaging station, Sturgis watershed 1, low discharge spring snowmelt runoff. The 120° V-notch weir carried 4.43 cubic feet per second (c.f.s.) at full head. Design discharge (25-year) is 45 c.f.s. The San Dimas flume will carry 53 c.f.s.

Table 2.--Annual precipitation, water yield, and "loss," Sturgis watersheds by water year (October 1 through September 30)

Water year	Watershed 1			Watershed 2			Watershed 3		
	Precipitation	Yield	Loss	Precipitation	Yield	Loss	Precipitation	Yield	Loss
	Inches								
1964	31.53	6.55	24.98	32.37	7.30	25.07	31.81	6.32	25.49
1965	34.84	12.85	21.99	34.28	13.62	20.66	34.70	11.94	22.76
1966	24.82	3.84	20.98	23.95	4.02	19.93	24.41	3.32	21.09
1967	32.35	14.29	18.06	31.85	14.53	17.32	32.28	12.36	19.92
1968	24.46	1.95	22.51	24.11	2.31	21.80	24.64	1.78	22.86
1969	21.18	3.22	17.96	20.59	3.63	16.96	20.94	3.36	17.58
Average	28.20	7.12	21.08	27.86	7.57	20.29	28.13	6.51	21.62
Standard error	2.21	2.14	1.11	2.30	2.17	1.23	2.25	1.88	1.12
				Percent 1/					
		25.3			27.2			23.2	

1/ Yield percent of average annual precipitation.

Seasonal Distribution

Both seasonal distribution and volume of yield are governed primarily by the amount and time of occurrence of spring and early summer precipitation, markedly different from the primary snowmelt dependency of most of the Rocky Mountain area. Precipitation reaches a minimum through the winter months November, December, and January (table 3), although snow accumulations through these months and into March may reach depths of several feet. Runoff during the interval November through February is insignificant in relation to annual yield (less than ¾ of 1 percent of total).

General thaw is common from the middle to the end of March. Though snowmelt yields relatively little channel flow, it is important for mantle recharge. Flow starts to rise in late March, on the average, and continues into April. The sharp increase in yield in April is due partially to melting of accumulated snow, but more a function of snow and rain falling duri the month (fig. 6). Flow does not reach maximu until May or June, long after all snow usua disappears.

Precipitation shows a substant increase from May to June and is maximum June, but flow does not show a proportio increase. Moisture goes into rapidly increasi evapotranspiration rather than into water yi (Orr 1959). Rain in the months of July, Augu and September goes almost entirely into eva transpiration rather than to water yield. T drop in yield during these months is mu greater proportionately than the drop precipitation.

The dominant role of April-June preci tation in water yield is illustrated by the fa that (1) 52 percent of total average ann precipitation falls during these months, and during this same interval the watersh produce from 92 to 94 percent of their to annual yield.

Table 3.--Average precipitation and runoff by month, Sturgis watersheds, water years 1964-69 inclusive

Month	Watershed 1			Watershed 2			Watershed 3		
	Precipitation	Runoff		Precipitation	Runoff		Precipitation	Runoff	
	Inches	Inches	Percent[1/]	Inches	Inches	Percent	Inches	Inches	Percent
Oct.	0.92	0.030	0.4	0.96	0.045	0.6	0.89	0.035	0.5
Nov.	.84	.014	.2	.82	.024	.3	.87	.017	.3
Dec.	.90	.004	.06	.86	.014	.2	.90	.010	.2
Jan.	.87	([2/])	--	.84	.011	.1	.93	.006	.09
Feb.	1.34	([2/])	--	1.23	.007	.09	1.37	.002	.03
Mar.	1.41	.084	1.1	1.20	.117	1.5	1.29	.101	1.5
Apr.	3.42	1.140	16.0	3.23	1.197	15.8	3.39	1.067	16.4
May	4.72	2.701	37.9	4.86	2.823	37.3	4.79	2.447	37.5
June	6.32	2.825	39.6	6.41	2.927	38.6	6.30	2.458	37.7
July	2.82	.262	3.7	2.84	.301	4.0	2.78	.276	4.2
Aug.	2.44	.047	.7	2.41	.067	.9	2.40	.070	1.1
Sept.	2.20	.021	.3	2.19	.042	.6	2.22	.033	.5
Total	28.20	7.129		27.86	7.577		28.12	6.521	

[1/] Monthly runoff percent of total annual runoff.

[2/] Trace.

Water Losses

The annual loss of water from the watersheds — the difference between precipitation input and water yield output (table 2) — closely represents total evapotranspiration. The aging controls are so well sealed to impervious bedrock that significant bypass leakage is highly improbable. There also is apparently very minor carryover effect from one year to the next. Judging from the very low base flow levels reached in late summer, all three watersheds have a low ground water storage capacity. Total yields during October through February have seldom been more than 1 percent of total annual yield.

The differences in losses between watersheds indicated in table 2 are small but may nevertheless be real. Watershed 3 shows the greatest loss during the study period. It also has the highest proportion of forested area, the largest total basal area and volume of timber per acre, and the greatest average depth and volume of soil. From these facts we can infer that evapotranspiration should be greater from watershed 3 than from watersheds 1 or 2.

The yearly distribution of losses is controlled by evapotranspiration stress. The stress, which is relatively low in winter and spring, increases sharply in early summer. Clues to relative water yield effectiveness of precipitation are apparent in comparing regressions of annual flow on precipitation in different parts of the year. For example, January-June precipitation was almost as closely correlated with total annual yield as with total annual precipitation. The January-May precipitation was even more closely correlated with annual yield than was either annual precipitation or January-June precipitation, and the improvement was substantial.

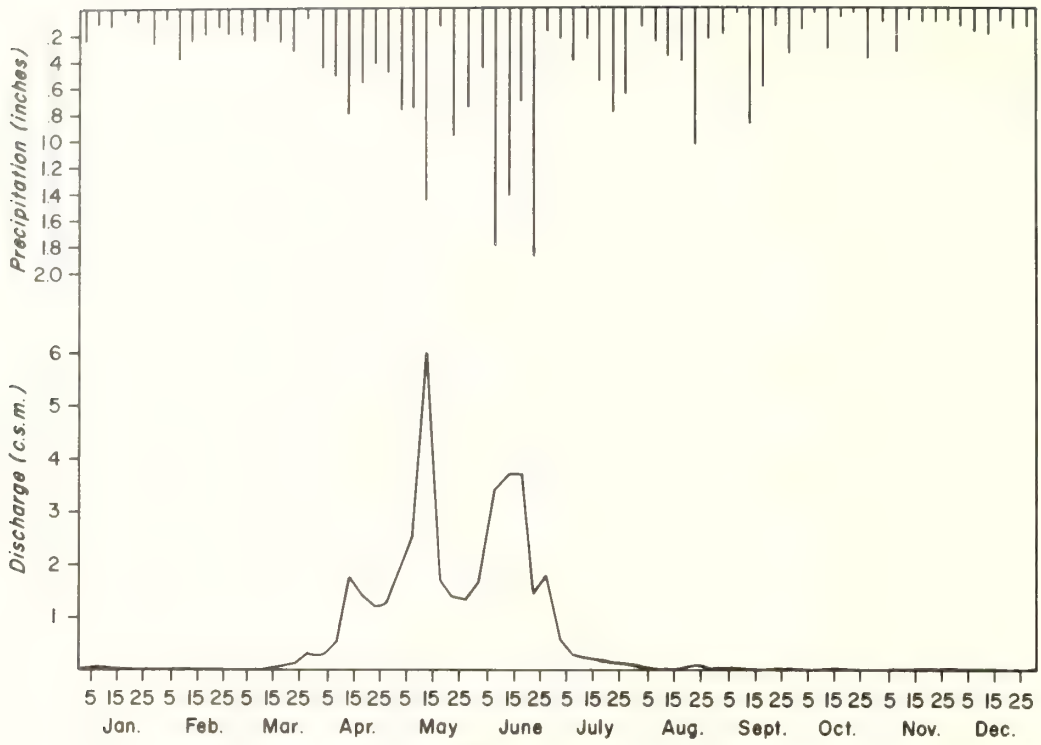


Figure 6.—Average precipitation and discharge in cubic feet per second per square mile (c.s.m.) for watershed 2, water years 1964-69, inclusive. Plotted values of both precipitation and discharge are for 5-day intervals.

Summary and Conclusions

Yield and general discharge characteristics of three small watersheds (217,89, and 190 acres) in the northeastern Black Hills are described. Yield has averaged close to 25 percent of precipitation through 6 water years — 1964-69. Snow is important for mantle recharge, but greatest water yield comes from rainfall in April, May, and June. During this period 92 and 94 percent of yield is produced from an average 52 percent of total annual precipitation. Average annual evapotranspiration on these watersheds, which have a low and hence relatively constant late-season moisture storage, is approximately 20.3 to 21.6 inches.

These results provide the most accurate and complete record of yield and flow characteristics of any small watersheds in the Black Hills. They are providing the basis for evaluation of forest stand manipulation water yield, as well as providing a significa step toward better general understanding watershed performance in the interior Bla Hills.

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1973. Water yield characteristics of three small watersheds in the Black Hills of South Dakota. USDA For. Res. Pap. RM-100, 8 p. Rocky Mt. For. and Range Exp. Stn., Fort Collins, Colo.

Three small forested watersheds (217, 89, and 190 acres) on the Vanocker laccolith in the northeastern Black Hills have yielded surface runoff equivalent to 7.12, 7.57, and 6.51 inches, or 25, 27, and 23 percent of average annual precipitation, water years 1964-69, inclusive. The gaging stations are well sealed on bedrock. Base flows are negligible. Hence, the net differences between input precipitation and measured outflow closely approximate yearly evapotranspiration. Data such as these provide for better understanding of the hydrologic behavior of pine-forested watersheds in the interior Black Hills, and thus provide criteria for more enlightened management prescriptions.

Keywords: Water yield, hydrology, evapotranspiration, Black Hills, *Pinus ponderosa*.

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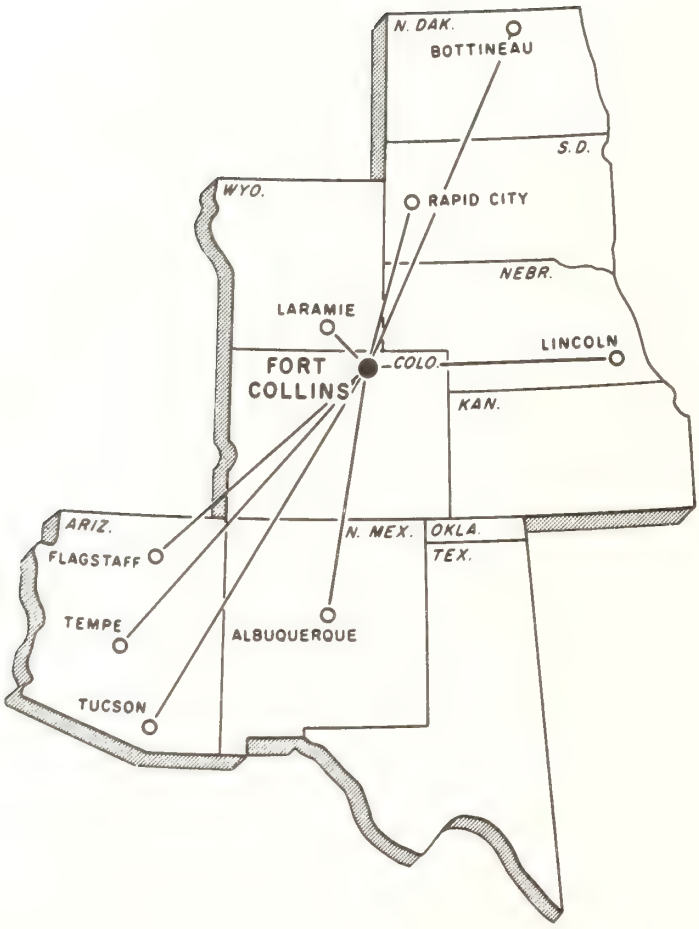
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REDICTING FIRE SPREAD
N ARIZONA'S OAK CHAPARRAL

y A. W. Lindenmuth, Jr.
nd James R. Davis

JUN 6 1973

bruary 1973
DA Forest Service
search Paper RM-101

Rocky Mountain Forest
and Range Experiment Station
Forest Service
U.S. Department of Agriculture

Abstract

Five existing fire models, both experimental and theoretical, did not adequately predict rate-of-spread (ROS) when tested on single- and multiclump fires in oak chaparral in Arizona. A statistical model developed using essentially the same input variables but weighted differently accounted for 81 percent of the variation in ROS. A chemical coefficient that accounts for effects of fuel chemistry on ROS is applied to the model. The model provides usable guidelines for predicting fire spread in Arizona oak chaparral.

Keywords: Arizona chaparral, fire spread, fire use, fuel chemistry.

USDA Forest Service
Research Paper RM-101

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Predicting Fire Spread in Arizona's Oak Chaparral

by
A. W. Lindenmuth, Jr., Principal Fire Behavior Scientist, and
James R. Davis, Associate Forest Fuels Scientist

Rocky Mountain Forest and Range Experiment Station[1]

[1]*Central headquarters maintained at Fort Collins, in cooperation with Colorado State University. Research reported here was conducted at Flagstaff, in cooperation with Northern Arizona University.*

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Predicting Fire Spread in Arizona's Oak Chaparral

A. W. Lindenmuth, Jr., and James R. Davis

Every person who has been involved with fire management is familiar with rate-of-spread (ROS)[2] indexes, meters, tables, models, and equations. More has been done and written about ROS than any other element of fire behavior, but none of the effort has applied specifically to oak chaparral in Arizona. The magnitude of fire behavior problems in the type is dramatically illustrated by the history of large and expensive-to-control wildfires, including the $2 million Battle fire in May 1972. This report summarizes and interprets the first research study of fire behavior in Arizona oak chaparral.

The study was concerned primarily with using fire as a tool for land managers. However, fire behavior is the same in both intentional and wildfires under the same conditions in oak chaparral.

Sections of this report deal with the study program, a description of the experimental area and research fires, a comparison of five contemporary ROS models with real-world research data, a new statistical model for predicting ROS, selection and use of fuel and weather variables, and discussion.

[2]*ROS in this report means forward movement of the fire head without spotting.*

Figure 1.--
Prescribed Fire Experimental Area, viewed from the north. Root-plowed firebreak surrounds entire area. Arrow indicates administrative site where laboratory, shop, and weather station are located.

Study Program

Research fires, ranging in size from single clumps of brush to ¼ acre were ignited in predominantly shrub live oak fuel *(Quercus turbinella* Greene). Of the 45 oak research fires ignited, 32 are suitable for analysis. The other 13 either went out or were rejected for technical reasons. Four larger evaluation fires were burned a year or more after the research fires to get comparison data for testing conclusions based on the smaller fires.

Experimental Area and Research Fires

Research fires were set on the Prescribed Fire Experimental Area, 30 miles east of Prescott on the Prescott National Forest, at an elevation of 4,750 feet (figs. 1, 2). Chaparral, or evergreen brush, covers about 8 percent of the total area of Arizona, or approximately 6 million acres. About

Figure 2.--
Trailer provides field laboratory and office space, and houses recorders for long-term weather data. Metal shed provides workshop-storage space, and houses LP gas-fueled electric generators.

85 percent is oak chaparral found normally at elevations from 4,000 to 5,500 feet. The largest block of oak chaparral surrounds the City of Prescott and the Experimental Area.

Average precipitation 1967-71, inclusive, was 16.05 inches; precipitation expected for Arizona oak chaparral is 13 to 16 inches (Nichol 1952). Average 1300-hour air temperature, all days, for June was 85° F. and for December 50° F.

The brush normally grows in clumps of some 10 to 30 feet in diameter. Fuels are fairly homogeneous within clumps, but change from clump to clump. Each clump is surrounded by a strip of virtually bare ground (fig. 3).

Polished stainless steel panels (each 4 feet by 10 feet) were erected around the sides of the research fires to control radiational and convective edge effects (fig. 3). An open passageway oriented with the wind allowed free movement of wind. The fire advanced on a straight line, edge-to-edge, as it normally would in a burning line of infinite length.

Each fire was ignited along the windward edge with a roll of excelsior (1 lb./lin. ft.) with electric squib-ignitor cord inserts at 3-foot intervals. After subsidence of the brief exaggerated flareup from massive ignition of both litter and crown, no trend toward either acceleration or deceleration was discernible.

All measurements were recorded electronically in an instrument trailer closeby. Measured variables that have been considered pertinent to ROS, from among more than 60 examined, are listed in table 1 with correlation coefficients, range, mean, and method of measurement.

Comparison of Contemporary Models with Research Data

These following five models fairly represent all research models conceived over the past 30 years to predict ROS. One of the important tasks of research is to test designed models under controlled conditions to determine how well they accomplish their objectives under a variety of conditions. We did this by measuring, on each research fire, the input required for each model and calculating predicted ROS. These were then compared statistically with actual ROS. We found that contemporary models are not suitable for predicting ROS under the fuel and climatic conditions prevailing in Arizona's oak chaparral.

The ROS model by Fons (1946) was derived experimentally by burning, in a wind tunnel, small constructed beds of (1) pine twigs set in a substrate like bristles in a brush, and (2) flat beds of pine needles. It treated spread as a series of ignitions of individual fuel particles. The model accounts for only 14 percent of the variation in ROS of the 32 research fires.

Byram's model (1959) was partly theoretical and partly empirical, based in some degree on longleaf and loblolly pine real-world research fires, in which Lindenmuth collaborated. It employed a relationship between flame length, available fuel, and heat of combustion of the available fuel. The model accounts for 48 percent of the variation in ROS, the best of any contemporary model, and performance can be improved appreciably by mathematical revisions.

Figure 3.--A typical research fire and area fuel distribution in oak chaparral on the Prescribed Fire Experimental Area, near Prescott, Arizona. Note the heat sink-thermocouple-radiation sensing package in the center of the burning line (feedout underground), heat flux transducer (horse), 35-mm camera and "midflame height" anemometer (right center), 16-mm time-lapse camera (on ladder), infrascope (on tripod), and power sprayer (to extinguish sample area at end of flaming combustion; lower left corner). Not shown are 36-foot tower (from which photo was taken) with another 16-mm time-lapse camera, and a 20-foot standard anemometer.

Table 1.--Summary of pertinent variables and correlations with measured rate-of-spread (ROS)

Description and variable	Unit of measure	Correlation coefficient[1]	Range in variable		Mean	Method of measurement
			Low	High		
Fuel consumed						
X_1 Flaming	lb./sq. ft.	0.45**	0.128	0.815	0.287	Representative stem sampling--percentage consumed by size classes
X_2 Total	lb./sq. ft.	.40*	.153	1.072	.407	
Fuel loading						
X_3 Total	lb./sq. ft.	.11	.229	1.597	.637	Representative stem sampling--mass by size classes/unit volume
	tons/acre		3.0	20.9	8.3	
Fuel moisture content						
X_4 Foliar	percent	.08	71.4	142.4	84.4	Random sampling--ovendrying
X_5 Litter, upper	percent	-.54**	4.3	17.9	8.1	
X_6 Litter, lower	percent	-.47**	5.4	26.5	10.9	
X_7 Dead stem	percent	-.59**	2.4	12.6	7.0	
Temperature						
X_8 Leaf	°F.	.43*	54	109	80	Thermocouples inserted in medium: air temperature in standard ventilated shelter--4.5 feet above-ground
X_9 Litter	°F.	.44*	48	115	79	
X_{10} Air	°F.	.44*	44	95	69	
Humidity						
X_{11} Relative humidity	percent	-.49**	7	67	21	Wet and dry bulb electro-aspirated psychrometer--standard ventilated shelter
X_{12} Saturation deficit	inches mercury	.42*	.098	1.438	.651	
Solar radiation						
X_{13} Net	ly/min.	.71**	.197	1.036	.741	Net radiometer
Wind velocity						
X_{14} At 20 ft. above canopy	m.p.h.	.34	4	19	8	Standard cup anemometer, low starting threshold
Fuel physics						
X_{15} Packing ratio		.20	.0019	.0123	.0047	Same as X_3
X_{16} Bulk density		.20	.0856	.5643	.2141	
X_{17} Surface area/volume ratio		.28	1259	2683	1742	
Fuel chemistry						
X_{18} Phosphates	percent	-.62**	.1740	.3913	.2917	Random sampling--quick frozen--freeze dried--standard lab analyses
X_{19} Potassium	percent	.14	.39	1.29	.62	
X_{20} Crude fat	percent	.31	3.0	6.9	4.9	
X_{21} Ash (silica not important)	percent	.34	3.3	10.9	6.3	

[1]Value must be $\geq$ .35 to be significant at 5 percent (*) level of probability and .45 at the 1 percent (**) level.

The problem with Byram's model is inputs. Inputs in a valid predicting model must be independent of the event to be predicted. Flame length and available fuel, which is the equivalent of fuel consumed, do not meet the requirement; they can only be measured during or after the fire for which ROS is to be predicted. The only alternative is to predict flame length and available fuel — in effect, resort to an inefficient and error-prone double prediction procedure to get to ROS.

Van Wagner's model (1967) is based on the concept that flame radiation is an important mechanism of heat transfer in the spread of fire. The principal components are flame length, weight of fuel, radiation intensity emitted by flame, proportion of radiation absorbed by fuel, fuel moisture, and angle between flame and fuel bed. The model accounts for 36 percent of the variation in the research data. Several components are dependent on the fires.

Rothermel's model (1972) follows the concept that ROS is proportional to the ratio of energy output to energy required to heat fuel to the ignition temperature. It is based in part on small laboratory fires. Fuel characteristics are heavily weighted. The latest version includes a variable moisture of extinction which does not work in Arizona oak chaparral. An earlier version with a constant moisture of extinction

accounts for only 12 percent of the variation in the research data.

The National Fire-Danger Rating model[3] is a modification of the Rothermel model; some fuel inputs are held constant, windspeed is calculated from velocity measured at 20 feet, and fuel loading is separated into "timelag" classes. This model accounts for 21 percent of the variation in the research data — the best performance of the models tested that do not include fire-dependent inputs.

A rate-of-spread model derived experimentally from relatively local situations will almost invariably outperform a similar model developed elsewhere or a broadly based theoretical model. This study has shown that to be the case in Arizona chaparral.

A theoretical model is used in the National Fire-Danger Rating System as a basis for the ROS prediction (Deeming et al. 1972). This and other predictions are transformed to dimensionless indexes because a relative measure is all that is required. Therefore, for the purposes of fire-danger rating, absolute errors are of no consequence as long as the relative changes are predicted so the performance is considered adequate. Fuel-type differences are described by fuel models which tailor the inputs to broad type classifications.

Both types of models have their places. A fire-use manager desiring more quantitative than relative predictions will have to rely for now on the somewhat narrower statistical models. Quite likely the data from empirical study will be useful in making the inputs for theoretical models more accurate, but there will always be a trade-off between definitive local applications and broad relative applications.

New Statistical Model

The statistical model was derived by correlation and regression analyses directly from the 32 research fires. Following are two versions (see table 1 for identity of X's; c.c.= chemical coefficient). The versions are essentially the same and account for 79 percent and 81 percent, respectively, of the variation in the ROS data, but inputs are handled differently.

[3]*Schroeder, Mark J., Michael A. Fosberg, James W. Lancaster, John F. Deeming, and R. William Furman. Technical development of the National Fire-Danger Rating System. (Unpublished report, dated Feb. 1972, on file at Rocky Mt. For. and Range Exp. Stn., Fort Collins, Colo.)*

Version 1:

$$Y = \left\{ 9.97 - 0.0399X_4 + 0.0586X_{10} - 0.1213X \right.$$
$$\left. + 6.483X_{13} + 0.3010X_{14} \right\} \left\{ \text{c.c.} \right\}$$

Measurements of air temperature (X_{10} relative humidity (X_{11}), and net radiation (X must be transformed (table 2). Because t contributions of these variables appear no linear, version one alternative is to transfo the variables and keep the model linear.

Table 2.--Transformation of variables for us in version 1 of new statistical mo

Air temperature (°F.)		Relative humidity (%)		Net radiatio (ly/min.)	
Measured	Transformed	Measured	Transformed	Measured	Tra for
40	20.0	4	4.5	0.45	0.
45	23.5	8	5.0	.50	.
50	28.5	12	6.5	.55	.
55	36.0	16	12.0	.60	.
60	46.0	20	20.5	.65	.
65	61.0	24	30.0	.70	.
70	83.0	28	38.0	.75	.
75	94.5	32	42.5	.80	.
80	98.0	36	45.5	.85	.
85	99.0	40	48.0	.90	.
90	99.1	45	50.0	.95	.
95	99.5	50	52.0	1.00	.
100	99.8	55	53.0	1.05	.
110	100.0	60	54.0	1.10	.

Version 2:

$$Y = \left\{ 26.1657 - 0.0335X_4 - 24.5608 \exp \right.$$
$$\left[- 0.06 \left(X_{10} / X_{11} \right) \right] + 14.1760X_{13}$$
$$\left. - 3.1394X_{13}^2 + 0.3526X_{14} \right\} \left\{ \text{c.c.} \right\}$$

$$\text{c.c.} = \left\{ 1 - 5.1196 \right.$$
$$\left. \left[1 - \exp \left(X_{18} - 0.235 \right) \right]^{.39} \right\}$$

Version 2 alternative is to build the tra formations into the model and enter the mo with directly measured values. Air temperat (X_{10}) and relative humidity (X_{11}) are combi into a single interaction term. The data sugg

nonlinearity in some of the variables, and it is reasonable to expect an interaction between these closely correlated variables. This version of the model appears somewhat more efficient than the other.

Chemical Coefficient (c.c.)

The chemical coefficient brings in the effect of fuel chemistry on ROS. This effect is discussed under "Selection and Use of Variables." The mathematical expression for the chemical coefficient is shown separately because fire managers are not expected to sample foliage and run analyses for phosphate content. Tabulated values are used instead (table 3). These are representative values based on a large number of chronologic samples.

Table 3.--Multiplying factor to correct ROS estimate for foliar phosphorus content under three conditions[1]

Month	Condition 1	Condition 2	Condition 3
March	1.0	2.2	2.2
April	1.0	1.6	1.6 (early)
			1.0 (late)
May	1.0	1.6	1.0 (early)
			1.6 (late)
June	1.0	1.7	1.7
July	1.6	1.6	1.0
August	1.7	1.0	1.0
September	1.0	1.0	1.0
October	1.0	1.0	1.0
November	1.0	1.0	1.0
December	1.0	1.0	1.0
January	1.0	1.7	1.7
February	1.0	1.8	1.8

[1]Condition 1: $\geq$ 3.00 inches precipitation preceding December + January; continue this column for 12 months, starting with March.

Condition 2: $\leq$ 3.00 inches precipitation preceding December + January; precipitation February + March < 3.00 inches; shift to condition 3 if February-March precipitation $\geq$ 3.00 inches.

Condition 3: < 3.00 inches precipitation preceding December + January; precipitation February + March $\geq$ 3.00 inches.

Model Restrictions

Litter and dead twigs ¼ inch or less in diameter must be reasonably dry for reliable predictions; 15 percent and less is satisfactory. Actual measurements are not necessary; variations in actual moisture content between 5 and 10 percent, the normal range during precipitation-free periods, have relatively little effect on ROS. Ordinarily this range of dryness will be reached within 5 consecutive days of clear seasonally warm weather April through October, and within 10 days during the remainder of the year.

Selection and Use of Variables

Variables were selected on a physical basis in order to cover a wide range of conditions. One form of each of the following variables was wanted: fuel moisture, temperature, humidity, wind velocity, solar radiation, fuel physics, and fuel chemistry. Another consideration was convenience in acquiring reliable data.

Slope was intentionally eliminated from the study by locating all plots on level or practically level ground. The interactions involved between slope and wind are complex and as yet unsolved. An attempt to solve this interaction would have added too much complexity to this initial study.

Fuel Moisture Content (X_4, X_5, X_6, X_7)

All ROS versus dead fuel moisture correlations (X_5, X_6, X_7) are highly significant. Any one could be used in a predicting model, but foliar moisture (X_4), although not significant in simple regression, is significant when included in multiple regression with weather variables to account for variation in ROS. Dead fuel moisture variables are also highly correlated with temperature, humidity, and net solar radiation; therefore, when a dead fuel moisture variable is introduced with these variables, it does not account for any significant reduction in residual variance. Dead fuel moisture alone cannot replace the weather variables, however.

Foliar moisture was selected over dead fuel moisture, but the latter must be retained in some form because of its limiting characteristics. Dead fuels do not burn vigorously, above 15 percent actual average moisture content, and normally cease to burn at approximately 25 to 30 percent. It is not feasible, due to interactions between variables, to build these limitations into the model now. Dead fuel moisture is retained as an external independent limiting factor.

Moisture content from a representative sample of leaves is needed for accurate predictions. Samples are thoroughly dried, but

without scorching, at 217° F. Moisture content is calculated as follows:

$$\left(\frac{\text{fresh weight - dry weight}}{\text{dry weight}}\right) 100$$

In the absence of actual data, ROS can be approximated roughly by using the appropriate representative moisture content (table 4).

Table 4.--Representative foliar moisture values for approximating ROS under three conditions[1]

Month	Condition 1	Condition 2	Condition 3
		Percent	
March	79	79	79
April	82	76	81
May	134	[2]74	82
June	96	[3]73	89
July	86	70	79
August	86	105	93
September	81	99	88
October	80	89	84
November	81	88	81
December	81	86	81
January	77	85	77
February	78	84	78

[1]Condition 1: ≥ 3.00 inches precipitation preceding December + January. Continue this for 12 months starting with March.

Condition 2: < 3.00 inches precipitation preceding December + January. Precipitation February + March < 3.00 inches. Shift to Condition 3 if February-March precipitation ≥ 3.00 inches.

Condition 3: < 3.00 inches precipitation preceding December + January. Precipitation February + March ≥ 3.00 inches.

[2]Considerable die-off of leaves is probable, thereby increasing flammability temporarily.

[3]Considerable shedding of leaves is probable, thereby decreasing flammability until new leaves harden in September or October.

Temperature (X_8, X_9, X_{10})

ROS is significantly correlated with leaf, litter, and air temperatures; each is important in the model. Air temperature is used for convenience, and measured 4½ feet aboveground in a standard ventilated shelter.

Humidity (X_{11}, X_{12})

Either relative humidity or saturation deficit should be included in the models. The former is selected for convenience and is measured in the same position as temperature.

Solar Radiation (X_{13})

Radiation, direct and indirect, flows to and from fuel at all times; the fraction retained by fuel at a particular instant is net radiation (langleys/minute). Because ROS is significantly correlated with net radiation, net radiation is important in the model.

Actual measured values at the site just prior to ignition are needed for accurate predictions. A net radiometer is exposed so the top face "sees" the sun and the bottom face "sees" the fuel. The radiometer generates a small electrical output proportional to the difference in temperature between the two faces. The output is measured with a millivolt meter, and converted to langleys/minute by means of a calibration chart.

In the absence of actual measured data, representative net radiation values (fig. 2) can be used to approximate ROS.

Wind Velocity (X_{14})

Average 20-foot velocity, above average vegetation crown profile, is the only expression of wind that needs to be included from among nine alternatives examined, including independent measurements at 4 feet aboveground and frequency of wind gusts.

Wind velocity does not show the strong effects on ROS usually attributed to it. An explanation is in order, based on case histories.

The fastest spreading research fire (46.25 feet per minute or 0.53 m.p.h., without spotting) *burned with average wind of 7 m.p.h.,* air temperature 95° F., relative humidity 15 percent, and litter moisture 4.5 percent (fig. 4). There was no opportunity to test higher wind velocities in other fires with conditions otherwise the same.

The *highest average wind velocity* for a research fire was *19 m.p.h.* with air temperature 76° F., relative humidity 16 percent, and litter moisture 6.6 percent. ROS was 31.54 feet per minute or 0.36 m.p.h., without spotting (fig. 5).

Wind velocity during the second fire was almost three times higher than in the first, yet ROS was only about two-thirds that in the first. Except for air temperature other variables were similar in both fires. This comparison illustrates the less-than-dominant influence of wind measured throughout the research fires.

Figure 4.--Although this was fastest spreading research fire, the flames (outlined for clarity) are standing up, in keeping with the relatively low windspeed.

Figure 5.--Flames are lying over, blown by relatively high wind, nearly three times as fast as in figure 4. However, rate-of-spread was only two-thirds that of faster fire.

What does the record show about wind? Briefly:

1. Wind is a limiting factor; a velocity of at least 7 to 8 m.p.h. is needed for fuel to burn well during favorable temperature and moisture conditions.
2. Wind is a provisional factor; increasing wind increases ROS *provided* temperature and moisture conditions are favorable for burning and do not regress.
3. When wind increases ROS without spotting, the increase is linear and amounts to about 4 inches per minute or 20 feet per hour for each additional m.p.h. in wind velocity. When spotting occurs, the ROS increases more rapidly, perhaps curvilinearly, with increasing windspeed.
4. During flaming, wind does not boost the percentage of fuel consumed appreciably, if any ($r = 0.04$, $b = 0.0044$). ROS and fuel consumed are closely correlated. Hence, failure of increasing wind to increase fuel consumed apparently is one reason why the effect of wind is limited in Arizona oak chaparral.

The 4-inch-per-minute increase in ROS for each additional m.p.h. in wind velocity (20 feet) is in line with recently published results from an independent study of ROS in slash fuels (Brown 1972).

Fuel Physics

$(X_1, X_2, X_3, X_{15}, X_{16}, X_{17})$

ROS is significantly correlated with fuel consumed, which is the equivalent of available fuel (X_1, X_2). Available fuel can be estimated reliably if fuel loading is accurately known, but a feasible estimating model for the latter is not yet ready. The correlation is not built into the model at this time.

Packing ratio (ratio of fuel volume to fuel bed volume, X_{15}), bulk density (ratio of fuel weight to volume, X_{16}), and surface area to volume ratio (X_{17}) apparently affect ROS. Effects were analyzed by fuel size components and for total fuel. None of these contributed appreciably in the multivariate analysis.

Within the range of fuel conditions among the research fires, the model works satisfactorily without fuel physics variables. Whether these variables will be needed for satisfactory operation throughout the entire oak chaparral type can be answered accurately only by experimentation over a broader range of fuel conditions.

Fuel Chemistry

$(X_{18}, X_{19}, X_{20}, X_{21})$

Content of phosphate phosphorus affects ROS appreciably, according to results from both these research fires and supporting laboratory burning tests. There is a critical threshold at 0.235 percent; with decreasing PO_4 below that level ROS increases, with increased PO_4 above the threshold there is no change in ROS. This pattern is built into the model as a coefficient or multiplier.

A model for predicting phosphate content is under development. Pending its availability, representative values (table 3) can be used for approximating ROS. It is not feasible now, or within the foreseeable future, to make chemical analyses part of fire management operations.

Crude fat and ash (both total and silica free) appeared to affect ROS of research fires, but these indications were not confirmed by laboratory burning tests. The sign of the ash correlation, although nonsignificant, is opposite to that found elsewhere (Rothermel 1972). For these reasons crude fat and ash are not in the model.

Discussion

The new statistical model is not perfect, but it is the most accurate and reliable operational predictor of fire behavior for the Arizona oak chaparral type. The variables used are about the same as in contemporary models; the change is essentially in weighting.

Contemporary models that give heavy weight to wind velocity, dead fuel moisture, and fine fuel moisture (composite of cured and green herbaceous material) predict an ROS that is too high for the cool half of the year (November-April) and too low for the warm half (May-October) in Arizona oak chaparral. Briefly, the reasons are that wind velocity, humidity, and dead fuel moisture (estimated by contemporary methods, which also are based primarily on relative humidity) are practically the same in both halves of the year. Relative humidities below 15 percent (1300 hour), for example, are common in both cool and warm months, which may surprise people not familiar with Arizona. ROS predictions based on wind and dead fuel moisture only, for precipitation-free periods, average about the same year-round. Because fine fuel moisture is notably higher in the warm half of the year (warm-weather growers predominate), inclusion of this variable appreciably lowers ROS predictions in the warm

half of the year. By comparison, fires burn much more vigorously and spread faster in the warm half, contrary to predictions based on wind, fuel moisture, and herbaceous condition.

The new statistical model corrects this significant anomaly by heavily weighting net radiation and air temperature, both of which have marked seasonal trends (figs. 6, 7). These variables also account for important day-to-day variations (note the range of these variables within months).

Predictions with the new statistical model were compared with actual ROS of four quarter-acre evaluation fires. Spread both within clumps and between a number of clumps across breaks of varying widths was measured. This small sample indicates that fires in broken, discontinuous fuel spread about 5 percent slower, on an average, than in continuous, relatively homogeneous fuel. Deviations of predicted from actual ROS were -1 percent, zero, +5 percent, and +18 percent. To better appreciate the significance of these deviations, it is worth noting that a test of another ROS model by Brown (1972) with small manmade slash plots showed deviations of predicted from actual of -14 to 580 percent, which he considered "reasonably close agreement."

How can the statistical ROS predictions be interpreted in fire management? Key ROS numbers are 10, 20, and 40, for level or slightly sloping areas. When predicted ROS is less than 10 (approximately), fuel probably will not burn well. Fire set repeatedly may spread through the litter and consume some aerial fuel, but it normally will not crown continuously through an individual clump or spread from clump to clump. Between 10 and 20 (approximately), individually ignited clumps probably will burn reasonably well, but fire normally will not spread from clump to clump continuously. Above 20, fire normally will spread from clump to clump continuously, and up to 40 will burn steadily, but not explosively. Above 40 (approximately), fire

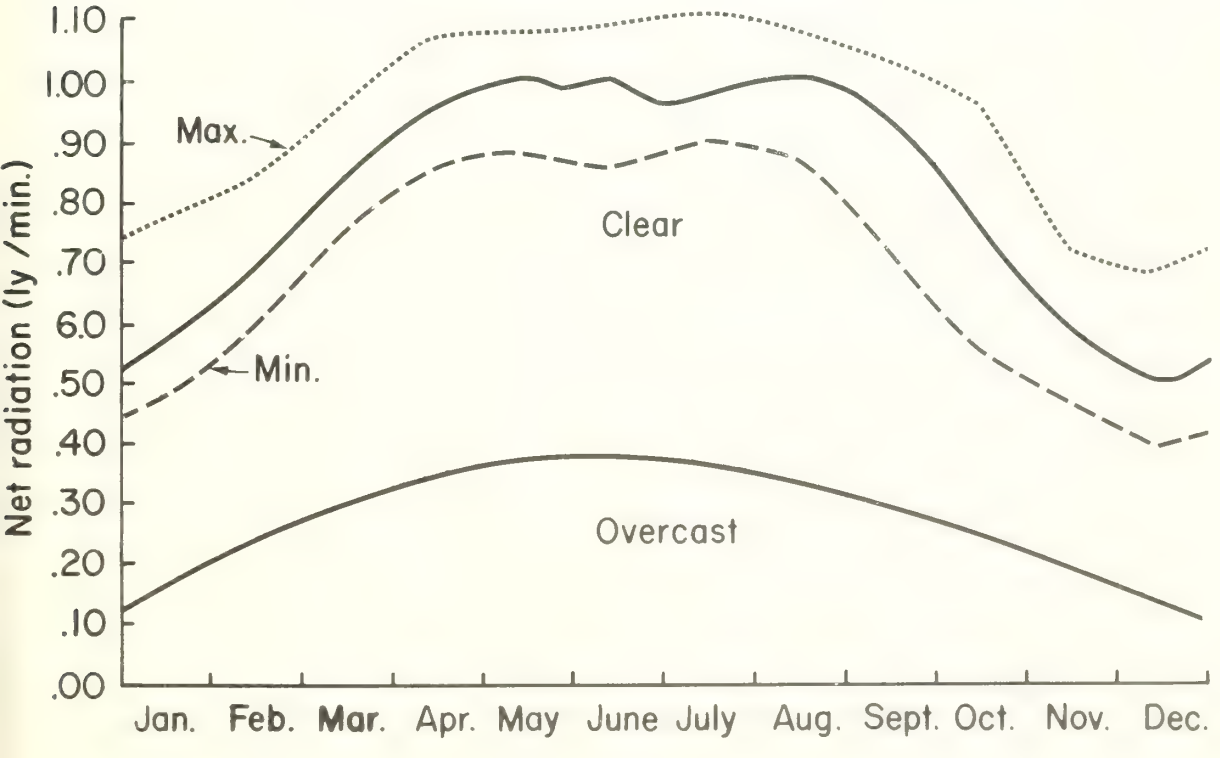

Figure 6.--Summarized net radiation values at 1300 hours for 1968-71, inclusive, at the Prescribed Fire Experimental Area may be used for approximating ROS. The atmosphere is relatively pollution-free over the Experimental Area; near sources of significant pollution, net radiation would be lower. The aberrations in the May-June period apparently result from atmospheric haze associated with drought and turbulence.

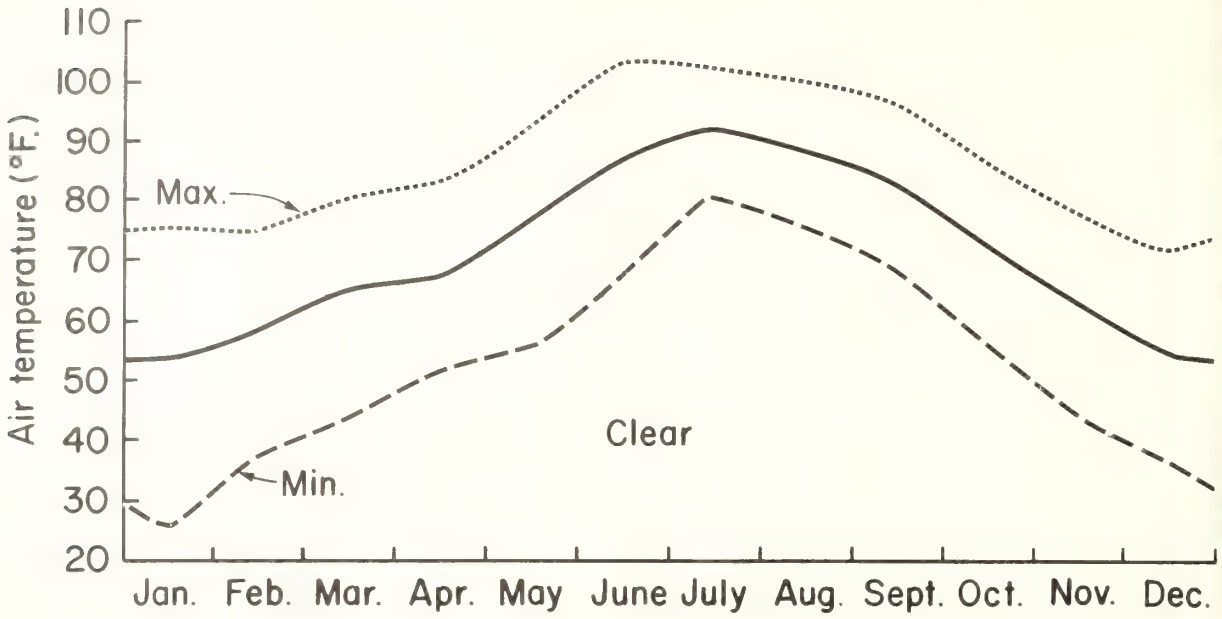

Figure 7.--Summarized air temperature values at 1300 hours for 1968-71, inclusive, at the Prescrib Fir Experimental Area may be used for approximating ROS in the absence of actual measurements.

probably will be flashy, normally too much so for prescribed burning. The key numbers must be adjusted downward where slope and/or spotting are factors.

People experienced in Arizona oak chaparral have always maintained that chaparral either burns fiercely or does not burn at all — no gradation in between. This rule of thumb is relatively accurate. The critical ROS threshold is around 20 feet per minute; conditions must be suitable for generating spread at or above that level before fire will spread across country. Thus the minimum sustained spread (without spotting) ever seen, usually in intentional fire, is about one-quarter mile per hour, and in wildfires normally one-half mile per hour or higher, because wildfires tend to occur during some of the worst conditions and commonly include spotting.

A 28,400-acre wildfire, May 14-20, 1972, on the Prescott National Forest provided an operational check of the statistical model and interpretations. The initial ROS, from 1215 to 1500 hours in a mixture of oak and manzanita chaparral, was scaled at 45 feet per minute, 1.25 feet per minute less than the fastest spreadin research fire. The wildfire included some shor range spotting and a variety of slopes and fue conditions. Predicted ROS was 40 feet per minut (based on data from tables 3 and 4, fig. 6) an measured temperature, relative humidity, an wind. The 11 percent deviation probably i attributable to spotting, favorable slope-win interaction during part of the run, and th admixture of manzanita. This fire wa unquestionably flashy.

The type of fire that does not spread fro clump to clump is potentially quite useful in lan management. It can be used to burn firebreak and small areas safely without bulldozing, brus smashing, and other special measures herete fore employed in intentional burning, a considerable cost both in dollars and sit disturbance. Forming fuelbreaks b nonspreading fire is feasible, economical, an effective, although additional research is neede to work out operational details. When designe to dissect large areas of chaparral, these break can substantially lessen the probability of larg catastrophic wildfires.

Fire managers must know more about fire behavior than ROS in order to use fire efficiently, however. Degree of fuel consumption, fire intensity, and level of byproduct emissions are other considerations.

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Lindenmuth, A. W. Jr., and James R. Davis.
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Five existing fire models, both experimental and theoretical, did not adequately predict rate-of-spread (ROS) when tested on single- and multiclump fires in oak chaparral in Arizona. A statistical model developed using essentially the same input variables but weighted differently accounted for 81 percent of the variation in ROS. A chemical coefficient that accounts for effects of fuel chemistry on ROS is applied to the model. The model provides usable guidelines for predicting fire spread in Arizona oak chaparral.

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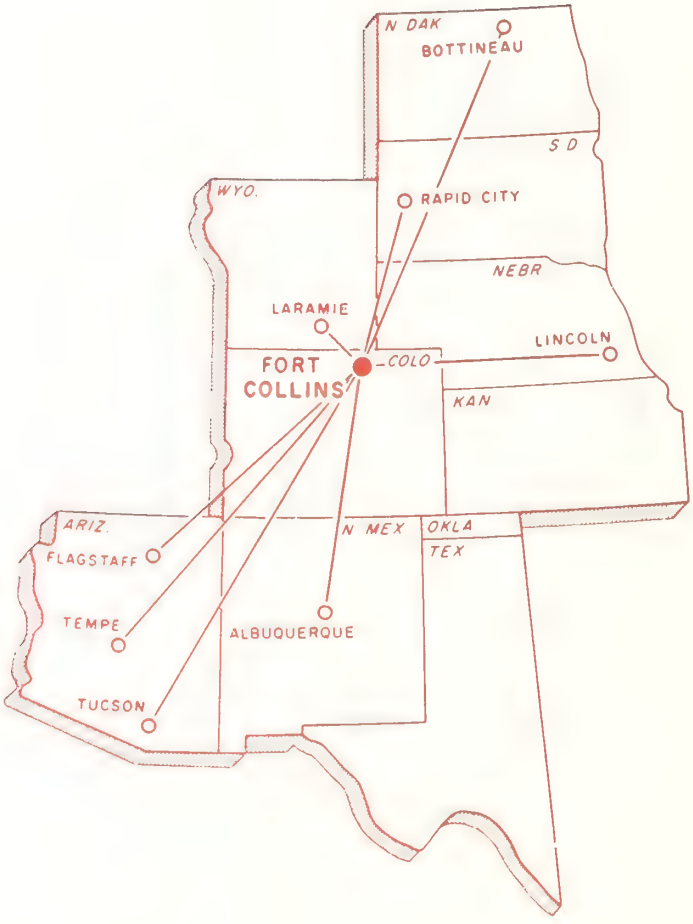
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FOREST STOCKING EQUATIONS: Their Development and Application

by Peter F. Ffolliott
and David P. Worley

March 1973

USDA Forest Service
Research Paper RM-102
Rocky Mountain Forest
and Range Experiment Station
Forest Service
U.S. Department of Agriculture

Abstract

Using point-sampling techniques, stocking conditions at a sample point can be described in terms of whether or not the point is stocked to a minimum basal area level corresponding to a particular basal area factor (BAF). Stocking equations relating proportions of a forest stocked to minimum basal area levels corresponding to each BAF used in an inventory can be defined by regression analyses. Stocking equations can be used to help evaluate land treatment potential, determine treatment feasibility on a single management unit, and as a basis for setting operating priorities on a number of management units.

Keywords: Stand density, basal area measurement, forest management, forest surveys.

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FOREST STOCKING EQUATIONS:
Their Development and Application

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David P. Worley, Principal Economist
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[1]*Research reported here was conducted at the Station's Research Work Unit located at Flagstaff, in cooperation with Northern Arizona University; Station's central headquarters maintained at Fort Collins, in cooperation with Colorado State University. Ffolliott is currently associate professor, Department of Watershed Management, University of Arizona, Tucson; Worley is with USDA Forest Service Northeastern Forest and Range Experiment Station's Unit at Columbus, Ohio.*

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FOREST STOCKING EQUATIONS: Their Development and Application

Peter F. Ffolliott and David P. Worley

Introduction

Point sampling techniques are widely used for inventorying forests. These inventories provide data on average basal area (or volume, number of trees, and so forth) per acre for forest managers. Such inventories may yield additional information regarding the proportions of a forest stand stocked to minimum basal area levels.

Even-aged stands with regular spacing patterns resulting from plantations or extended periods of management can, possibly, be described by average basal area per acre. With uneven-aged stands of irregular spacing patterns, however, another statistic — the proportion of the stand stocked to a minimum basal area level — would be useful to set realistic limits for forestry practices, judge suitability of an area for management practices, or set priorities for cultural or harvesting operations among forest areas. Such information can be derived from stocking equations, as described here.

The purposes of this paper are to: (1) outline the theory behind the development of stocking equations, (2) illustrate the methodology of stocking equation synthesis, and (3) demonstrate applications of stocking equations in forest management decision-making.

Theory Behind Development of Stocking Equations

The basic theory of point sampling is well known. The number of trees tallied at a sample point, multiplied by the basal area factor (BAF) used, gives an estimate of basal area per acre at that sample point. A sample point is stocked to basal area levels of 50, 70, and 100 square feet per acre on the basis of 5, 7, or 10 trees tallied with a BAF of 10. Estimates from a number of sample points are averaged to estimate the basal area of the forest area.

The use of a single BAF can incorrectly describe the stocking situation at a single point, however, due to irregular spacing patterns and the variety of tree sizes frequently associated with natural timber stands (fig. 1). For example, a sample point would be considered stocked to a basal area level of 75 square feet if three trees were tallied with a BAF of 25. But, it is possible that no trees would be tallied with a BAF of 75, in which case the sample point would not be considered stocked to 75 square feet. Conversely, assume one of the three trees tallied with a BAF of 25 is close enough to the sample point to be tallied with a BAF of 100. The tally with a BAF of 25 would underestimate this stocking condition.

Empirical trials in cutover ponderosa pine stands in Arizona corroborate the above examples. Sample points with a single tree

Figure 1.—Irregular spacing patterns and intermixed size classes in Arizona ponderosa pine stands.

tallied with a BAF of 25 were also stocked with a BAF of 50 and 75 half the time. Sample points stocked with two trees with a BAF of 25 were stocked, with a BAF of 50, only 84 percent of the time, and sample points stocked with three trees with a BAF of 25 were stocked with a BAF of 75 only three-quarters of the time.

If it is not possible to correctly describe stocking conditions at a single sample point with a single BAF, it follows that it may not be possible to describe the proportion of a forest stand stocked to arbitrarily specified basal area levels. A more accurate method for determining the proportion of a stand stocked to different basal area criteria is through the use of stocking equations. The synthesis of stocking equations is based on two assumptions.

First, a sample point is considered stocked to a given minimum basal area level if at least one tree is tallied with a BAF corresponding to that level, or not stocked at that level if no trees are tallied. This concept about stocking conditions has been suggested as a way of determining the proportion of a stand stocked to a single minimum basal area level defined by a specified management objective (Roberts 1964). In the absence of specific management guidelines, an inventory system employing a range of BAF's, allowing sample points to be described in terms of being stocked to a corresponding range of minimum basal area levels, is advantageous.

Secondly, the proportion of a forest stand stocked to a given minimum basal area level can be estimated from the proportion of sample points stocked to that minimum level, provided the sampling of stocking conditions was unbiased. Similarly, relationships can be established between proportions of a stand stocked to minimum basal area levels corresponding to each BAF used in the inventory. These relationships assume mathematical forms which can be defined empirically through regression analyses. The equations describing these regressions are stocking equations, the dependent variable being the proportion of a forest stand stocked to minimum basal area levels within limits dictated by the BAF's used in the inventory.

Synthesis of Stocking Equations — An Illustration

To illustrate methodology, stocking equations have been developed to describe cutover and virgin ponderosa pine *(Pinus ponderosa* Laws.) stands in north-central Arizona.

Study Areas

Data representing a cutover ponderos pine stand were collected from watershed 1 encompassing 425 acres, on the Beaver Cree watershed (Brown 1971), 45 miles south Flagstaff. At the time of measurement, half the merchantable sawtimber volume had bee cut from the area between 1943 and 195 Sawtimber volume averaged 3,700 board feet p acre, and the site index (Meyer 1961) varied fro 45 to 60 feet at 100 years. Soils, derived fro basalt parent material, are classified in t Brolliar and Siesta-Sponseller soil manageme areas (Williams and Anderson 1967). The ar was sampled with 197 points arranged in fo random starts with four strata (Shiue 1960).

Data from a virgin ponderosa pine sta were collected on the Long Valley Experiment Forest, 65 miles southeast of Flagstaff. At t time of the study, this was one of the fe remaining areas in Arizona where a virgin sta could still be found on a good timber-growi site. Timber on the 1,280 acres comprising t Forest was uneven-aged, with different a classes occurring as small, even-aged grou Sawtimber volume averaged 20,500 board fe per acre, and the site index (Meyer 1961) was to 90 feet. Soils, formed from limestone and sa stone, are classified in the Hogg-McVick series (Anderson *et al.* 1963). One hundred six six points arranged in an 8-chain by 8-chain g provided the sample design here.

Methods

Sample points on both study areas w considered stocked or not stocked on the basis trees tallied with an angle gage correspondin BAF's of 5, 10, 25, 50, 75, 100, 125, 150, 175, 2 and 250. Diameters (d.b.h.,o.b.) of all tallied tr were recorded to allow subsequent assignm into size classes.

The data were subjected to regress analyses to develop stocking equati describing (a) all size classes and (b) individ size classes on the two study areas. Lin regressions had been used previously to descr the proportions of a cutover ponderosa p stand stocked to minimum basal area lev between 25 and 75 square feet (Ffolliott Worley 1965). Here, straight-line predict mechanisms performed well over a limited ra of basal area levels. More complex curvilin forms were required, however, for regressi that defined stocking conditions near extremes of a stand population — low or h stocking levels for all timber size class eleme within a stand — or for particular size-cl

components. Furthermore, several scatter diagrams revealed an inflection point near the Y-axis. Consequently, commonly used linear transformations proved unsatisfactory.

A computer program (Jameson 1967) that approximates a 5-parameter transition growth curve describing general sigmoidal relationships (Grosenbaugh 1965) was arbitrarily selected to illustrate the development of stocking equations. Other mathematical models and computer programs designed to produce a sigmoid form might give similarly good results. As a practical matter, the closeness of fit to the data illustrated in figure 2 suggests hand plotting may be adequate for developing curves for many purposes.

Results

Stocking equations describing all size classes of ponderosa pine on the two study areas are illustrated in figure 2. Stocking equations developed for the sawtimber (at least 11.0 inches diameter), pole (4.0 to 10.9 inches diameter), and sapling (less than 4.0 inches diameter) size classes (fig. 3) are summarized as follows:

Beaver Creek (watershed 12)

(1) Sawtimber

$$Y = 100 - 89.1\ (1-e^{-0.\cdot 19x})^{1.\cdot 1}$$

(2) Poles

$$Y = 100 - 89.2\ (1-e^{-\cdot.\cdot 1\cdot\cdot})^{1.\cdot 1}$$

(3) Saplings

$$Y = 100 - 103.8\ (1-e^{-0.009x})^{0.25}$$

Long Valley Experimental Forest

(1) Sawtimber

$$Y = 100 - 24.1\ (1-e^{-0.001x})^{0.75}$$

(2) Poles

$$Y = 100 - 96.5\ (1-e^{-0.008x})^{0.\cdot 1}$$

(3) Saplings

$$Y = 100 - 101.1\ (1-e^{-0.\cdot\cdot 3x})^{0.\cdot 5}$$

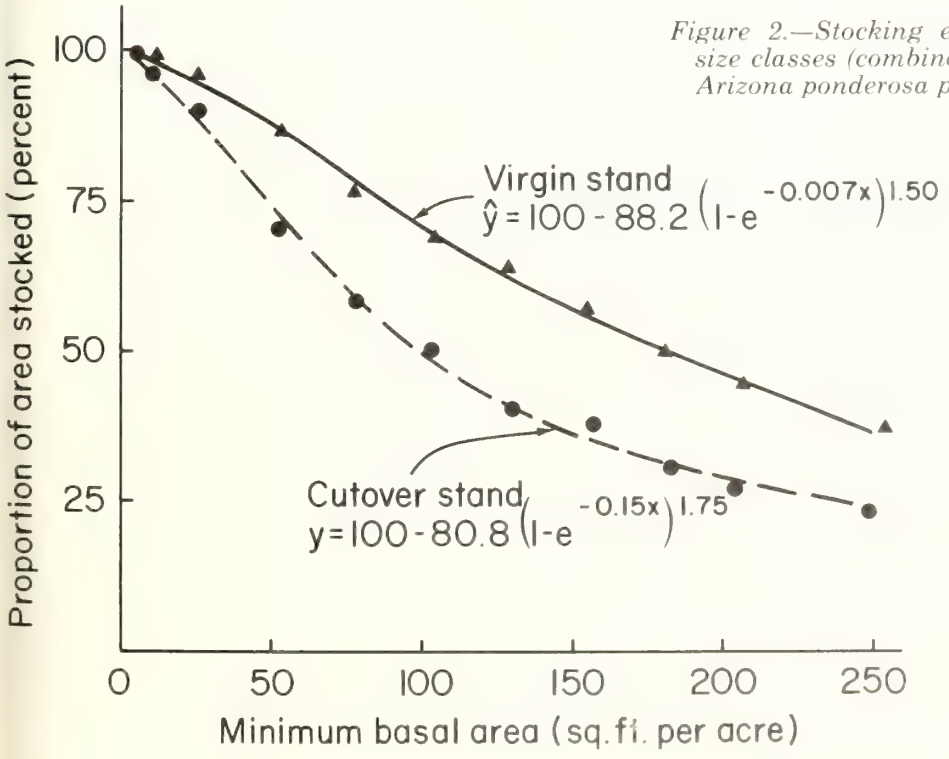

Figure 2.—Stocking equations describing all size classes (combined) in virgin and cutover Arizona ponderosa pine stands.

Summation of the three size-class components at a given basal area level may exceed the stand population stocking at that level, since many sample points were stocked with more than a single size class.

The stocking equations allow us to estimate the proportion of a forest stand stocked by a stand element to minimum basal area levels up to 250 square feet. Solving stocking equations for numerous alternative basal area levels may

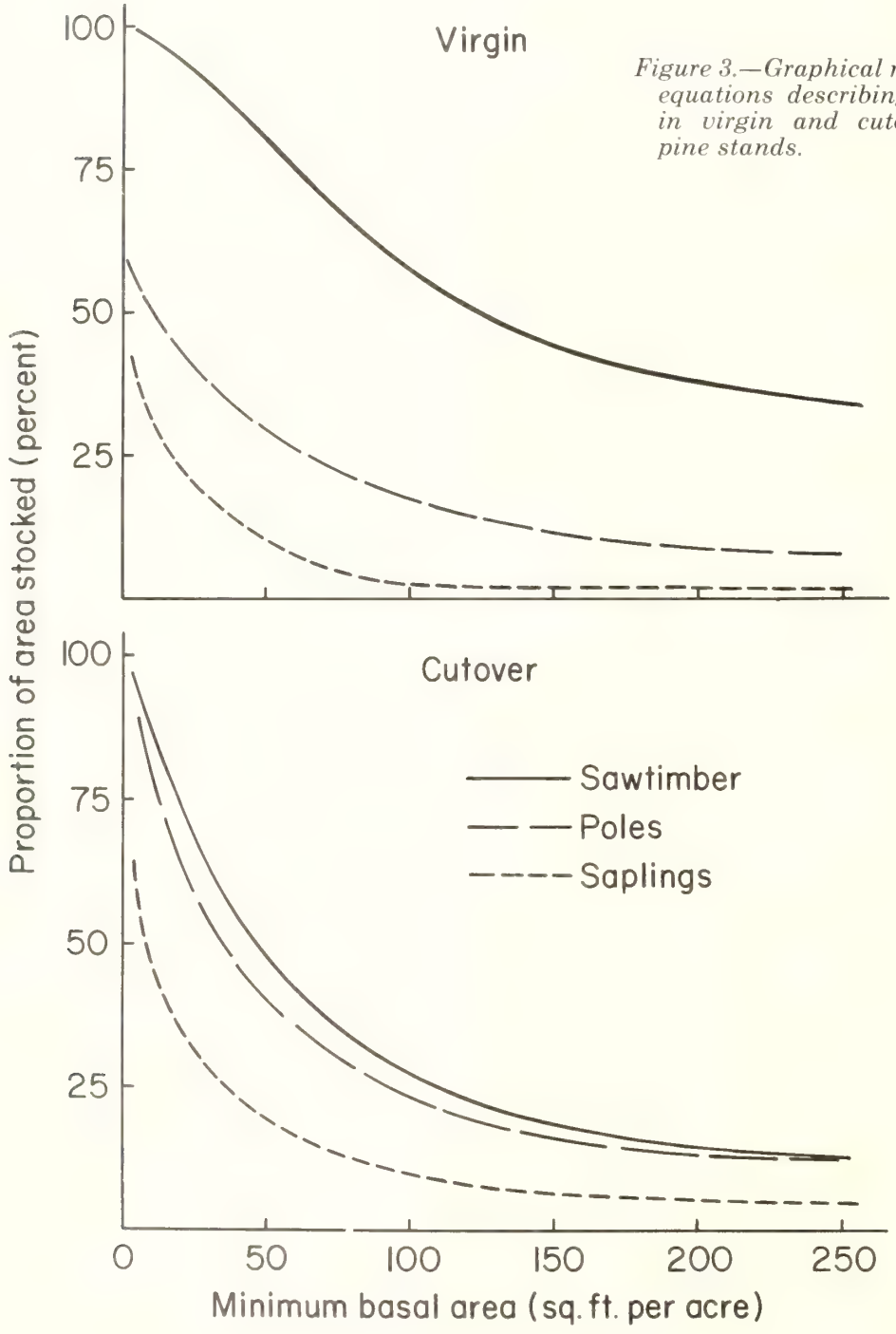

Figure 3.—Graphical representation of stocking equations describing individual size classes in virgin and cutover Arizona ponderosa pine stands.

become time consuming. To ease computations, a supplementary computer program can be written to solve equations in terms of the proportions of a stand stocked to any intermediate basal area. Generally, estimates obtained from a graphical presentation of the stocking equation will suffice.

Applications of Stocking Equations

A truly adequate description of the characteristics of timber on a management unit must answer a variety of questions of management specialists regarding timber production. Stocking equations help provide such answers, by defining the proportion of a forest stand on a management unit stocked to minimum basal area levels dictated by management objectives.

Setting Realistic Limits for Forestry Practices

Stocking equations can help a manager reach a decision as to the feasibility of imposing a treatment (such as harvesting, thinning, and so forth) on a management unit. It is assumed that the proportion of a forest stand stocked to a minimum basal area level which corresponds to the basal area level prescribed by treatment will, subsequently, represent the proportion of the stand that will be placed under treatment.

For example, suppose a silvicultural practice calls for a uniform thinning of all sawtimber in a forest stand to a basal area level of 50 square feet per acre, the assumed "optimum" in terms of a sawtimber management potential. However, a stocking equation developed for the management unit may reveal only 43 percent of the stand could meet the treatment stocking objective (fig. 4). A decision may then need to be made regarding treatment feasibility. Possibly, the original prescription could be discarded in favor of one that would place a larger proportion of the stand on the management unit under treatment. This could be achieved by reducing the uniform thinning treatment to 25 square feet per acre. Unfortunately, thinning to this alternative stocking level may result in a lower sawtimber management potential. Due to the greater proportion of the area treated (fig. 4), however, the outcome could be more favorable in the long run. The final decision must be a compromise between obtaining the maximum management potential,

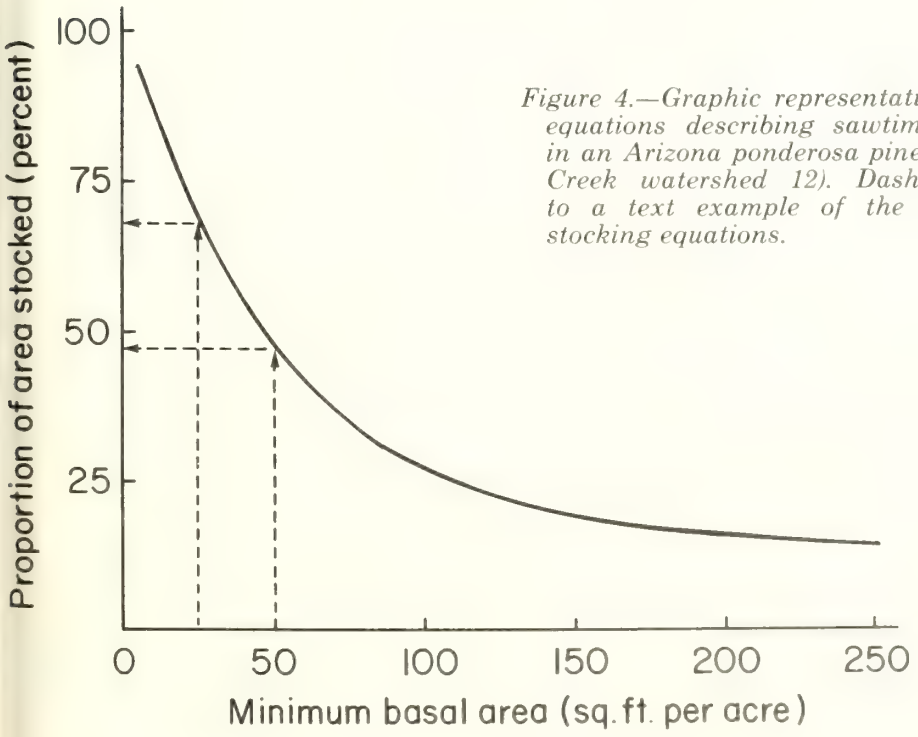

Figure 4.—Graphic representation of stocking equations describing sawtimber size class in an Arizona ponderosa pine stand (Beaver Creek watershed 12). Dashed lines refer to a text example of the application of stocking equations.

as prescribed by treatment, and extending the treatment to the largest possible proportion of the stand on the management unit.

Regardless of what a specific land treatment is to accomplish, the application of stocking equations will help evaluate treatment potential and prescribe treatment feasibility. A range specialist may ask "What proportion of a management unit is stocked in excess of a given basal area level considered maximum to allow acceptable forage production for allotment management?" An economist interested in costs might ask "How much of a management unit needs to be treated, and to what intensity does the treatment need to be applied, to bring the tract to a prescribed stocking level?" A timber manager might need data describing the extent of merchantable sawtimber to a basal area level considered the minimum for profitable harvesting.

Decisionmaking at Different Levels of Interest

If the "optimum" basal area level criterion for sawtimber management potential is 50 square feet per acre, we saw (fig. 4) that 43 percent of the management unit described above would meet the treatment stocking objective. This elementary type of statistic might be called primary, or at the first level of interest.

If the sampling intensity is great enough, other levels of interest can be exploited from stocking equations. Our timber manager might ask "If 43 percent of the management unit meets the sawtimber treatment prescription, how much of this latter area will be stocked with residual trees of submerchantable size?" This is an example of a secondary level of interest. Source data from the proportion of the management unit that meets the treatment prescription can be subjected to regression or graphic analysis. For our example, the proportion of the management unit that meets the sawtimber treatment prescription stocked with submerchantable ponderosa pine at various minimum basal area levels is:

Basal area of submerchantable ponderosa pine (Sq. ft./acre)	Cutover area stocked (Percent)
20	82
40	69
60	59
80	50
100	42

The above information could provide the basis for scheduling planting or determining site preparation costs. For instance, if 60 square feet of basal area per acre is judged satisfactory stocking for advanced regeneration after cutting, 59 percent of the proportion of the management unit that meets the sawtimber treatment prescription is already stocked, and reproduction measures need be planned for 41 percent.

Setting Operating Priorities

The output of stocking equations — the proportion of a management unit stocked by a stand element to a specified criterion — can be used with other information to set management priorities. This can be illustrated by an example.

Ten Beaver Creek watersheds, similar to watershed 12, were inventoried so that stocking equations, and timber volume information could be developed. Let us rank these watersheds according to the desirability of harvesting ponderosa pine sawtimber to achieve the "best release" of pole-sized ponderosa pine trees and a minimum release of a timber "weed" species, Gambel oak *(Quercus gambelii* Nutt.). Direct information, obtained from the stocking equations, is the proportion of each watershed stocked with pole-sized ponderosa pine, and the proportion of each watershed stocked with Gambel oak. Selected criteria are: (a) a minimum sawtimber cut of 1,000 board feet per acre, (b) at least 25 percent of the watershed stocked with pole-sized ponderosa pine at a minimum basal area level of 50 square feet per acre, and (c) no more than 25 percent of the watershed stocked with Gambel oak at a minimum basal area level of 50 square feet per acre. This information is arrayed in table 1.

The application here combines the area information — the output of stocking equations — with sawtimber volume estimates to determine cutting priorities. Individual watersheds are eliminated from consideration when they do not meet one or more criteria. Those remaining are ranked on a sawtimber volume basis. They could be ranked on any combination of the above three criteria which could be shown to maximize benefits or minimize costs.

Development of Distribution and Density Functions

The relationships defined by stocking equations are exceedance curves, which describe the proportion of a stand stocked to minimum basal area levels. Distribution functions, which

Table 1.--Priorities for harvesting large sawtimber

Watershed	Sawtimber volume	Area stocked at minimum of 50 square feet of--		Feasibility limits (a,b,c)[1/] and priority rankings (1,2,3)
		Pole-sized ponderosa pine	Gambel oak	
	Bd.ft./acre	- - - - Percent - - - - -		
A	2,800	29	16	2
B	3,110	38	23	1
C	830	26	13	Insufficient volume
D	1,660	22	26	Insufficient poles; too much oak
E	1,230	29	31	Too much oak
F	2,410	29	22	3
G	1,470	18	38	Insufficient poles; too much oak
H	2,290	16	16	Insufficient poles
I	1,830	27	28	Too much oak
J	570	46	13	Insufficient volume

[1/] Limiting criteria: (a) a minimum sawtimber cut of 1,000 board feet per acre;
(b) at least 25 percent of the watershed stocked with pole-sized ponderosa pine at a minimum basal area level of 50 square feet per acre;
(c) no more than 25 percent of the watershed stocked with Gambel oak at a minimum level of 50 square feet per acre.

describe cumulative frequency, can be readily developed from these relationships if desired. With distribution functions, it would be possible to derive density functions, which define the probabilities of obtaining a small interval of forest stocking considered prerequisite to imposing a land treatment. Estimates of these probabilities can be of value in decisionmaking at the first level of interest.

Summary and Conclusions

1. Using point sampling techniques, stocking conditions at a sample point can be described in terms of whether or not the point is stocked to a minimum basal area level corresponding to a particular BAF.
2. Mathematical relationships between proportions of a forest stand stocked to minimum basal area levels corresponding to each BAF used in an inventory can be defined through regression analyses. The equations describing these regressions are stocking equations; the dependent variable is the proportion of a forest stand stocked to a given minimum basal area level, and the independent variable is the minimum basal area level.
3. Stocking equations describing cutover and virgin ponderosa pine stands in Arizona were developed by means of a computer program that approximates a sigmoidal relationship. These equations define the proportion of these two stands stocked to minimum basal area levels up to 250 square feet per acre.
4. Stocking equations can be used to help evaluate land treatment potential, to determine treatment feasibility on a single management unit, and as a basis for setting operating priorities on a number of management units.
5. To apply this technique, the land manager must have a multiple BAF inventory made for the management unit in question, then prepare stocking equations or graphs similar to those described here.

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Using point-sampling techniques, stocking conditions at a sample point can be described in terms of whether or not the point is stocked to a minimum basal area level corresponding to a particular basal area factor (BAF). Stocking equations relating proportions of a forest stocked to minimum basal area levels corresponding to each BAF used in an inventory can be defined by regression analyses. Stocking equations can be used to help evaluate land treatment potential, determine treatment feasibility on a single management unit, and as a basis for setting operating priorities on a number of management units.

Keywords: Stand density, basal area measurement, forest management, forest surveys.

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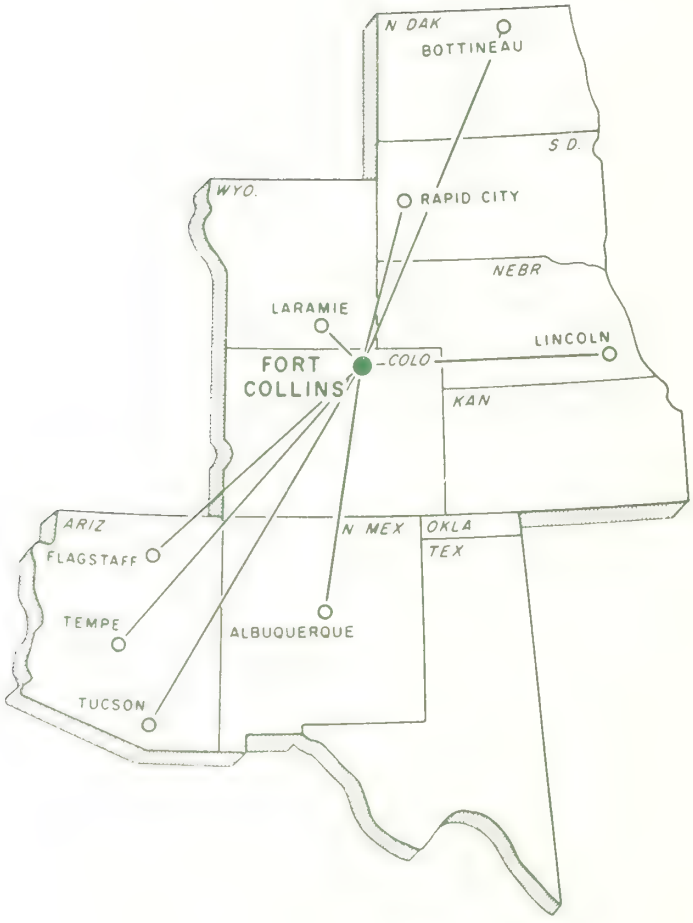
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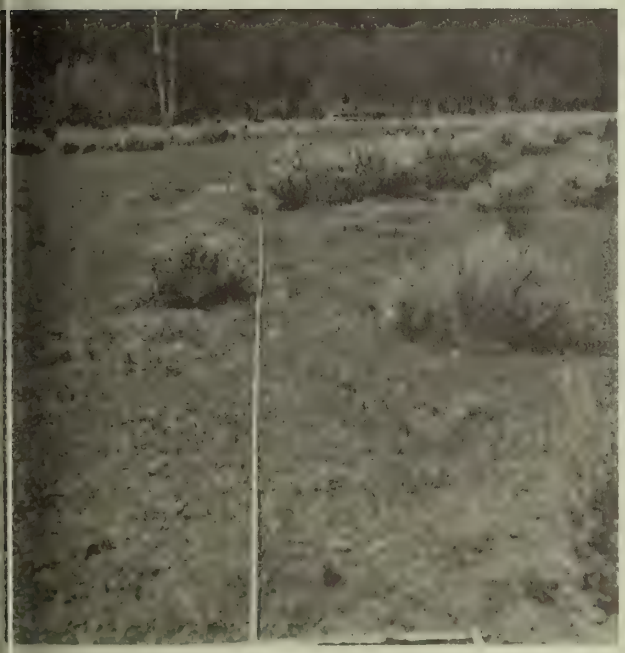
INTERPRETATION OF TREND IN RANGE CONDITION FROM 3-STEP DATA

By Jack N. Reppert
And Richard E. Francis



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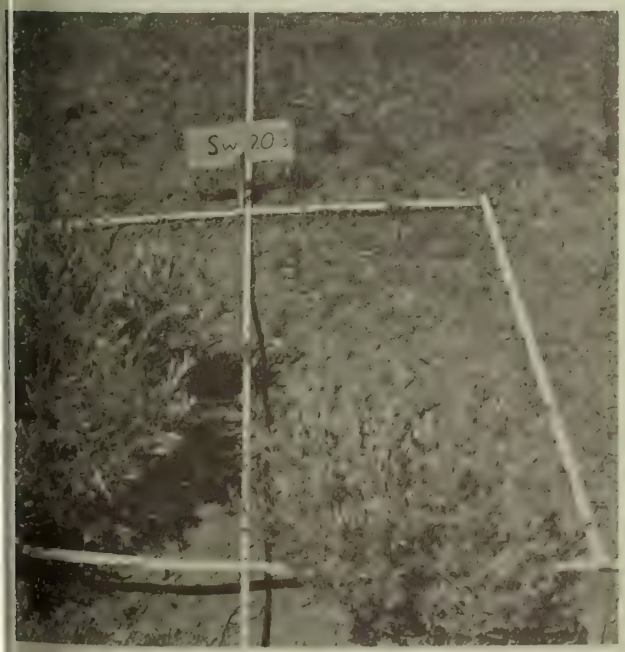

Abstract

The 5-phase procedural framework uses 3-step range trend data to identify important trends in vegetation and soil characteristics and assign cause. Fieldwork is executed under strict procedural rules (phase 1), and current condition and tentative trend are determined (phase 2). Office statistical tests of change in frequency of important species groups, species, and soil surface factors are related by photointerpretation to visible changes in other important indicators of range trend (phase 3). All characteristics that indicate change are grouped and related to trends judged in the field (phase 4), and all available supplemental information is considered and most probable cause(s) of trend assigned (phase 5).

KEYWORDS: Range management, indicator plants, groundphotointerpretation, range plant frequency, 3-step method.

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Interpretation of Trend in Range Condition from 3-Step Data

by

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Rocky Mountain Forest and Range Experiment Station[1]

[1]*Forest Service, U. S. Department of Agriculture, with central headquarters maintained at Fort Collins, in cooperation with Colorado State University.*

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Interpretation of Trend in Range Condition from 3-Step Data

Jack N. Reppert and Richard E. Francis

Background

Presently, there are 11,908 grazing allotments administered by the Forest Service which, among other important uses, furnish forage and browse for livestock, game, and other animals. Within these allotments are many complex range sites classed within broad vegetation types. These sites vary in range condition. One responsibility of range examiners is to know the current condition of these range sites and, over the years, to be aware of trends in condition. The objectives are to prevent deterioration of the range resource, and encourage application of appropriate management strategies to improve condition. This Paper describes how a skilled range examiner may use the 3-step method to interpret trend in range condition.

The 3-step method for measuring trend in range condition was developed by the USDA Forest Service for administrative use after 3 years of intensive study from 1948 through 1950 (Parker and Harris 1959). Under the direction of K. W. Parker, National Forest Systems range examiners from various Regions modified and adapted research contributions to help build a practical procedure. The Forest Service adopted the 3-step method as part of its range analysis program in 1956, and many other agencies since have adopted it.

Within the Forest Service, the method has been modified. However, the three fundamental steps remain intact: (1) Measure vegetation and soil stability on permanent transects grouped in clusters of one to three transects, (2) summarize data and classify current range condition and trend in the field, and (3) take two oblique ground photographs for permanent visual record. The procedural details for measurement are familiar to all who have used the method or have read Parker's 1951 and 1953 papers.

A cluster is permanently located on an area; periodic remeasurement (often at 5-year intervals of certain plant and soil characteristics along with ground photographs provide data to infer trend in range condition. Clusters are used as benchmarks on key areas, similar to listening posts on a battlefield. A key area is representative of a portion of primary range and, by location, is sensitive to changes in management practices. By 1967, over 16,500 permanent 3-step clusters had been established on 5,307 allotments within the six western Regions.

Difficulty in Interpretation of Trends

The 3-step method was designed so that trained range examiners could establish many clusters and collect data rapidly. The more difficult part came later when the range examiner had to explain changes in the data, visible changes in the photos, or changes in the condition scorecard values. This difficulty has long been recognized. In 1957, Parker wrote in a memo to the file, "At the onset of the trend study we recognized that interpretation of data would be the most difficult problem."

A range examiner expected to interpret range trend must be a highly trained ecological investigator, who is able to understand much about the situation as he currently examines it and compares it with previously collected data. It is seldom easy to determine range trend direction, state the cause, and recommend proper management action. Several reasons for this difficulty are:

1. Trend is evaluated over many years. During passage of time, transects may be destroyed, or moved, data lost, condition standards changed, and management objectives shifted.
2. The range examiner who remeasures a 3-step cluster is seldom the person who made the previous measurement and, except for photos, often has never seen the cluster before.
3. Many clusters measured on a 5-year interval are not visited the second, third, and fourth years so that a trend-causing agent (effects of weather, insects, or disease in intervening years) may go unnoticed and undocumented.
4. Highly skilled range examiners are not always available to remeasure and interpret the data.

Frequency — What It Is and How It Can Be Used

Three-quarter-inch loop-frequency is the most consistently used measurement in the 3-step method. Frequency is the chance of finding a plant species or nonplant factor within a sample area in any one trial (Greig-Smith 1964). When no plant occurs within the loop, the soil surface factor covering most of the loop area is recorded. Frequency is measured at 1-ft intervals along 100-ft transects which form a cluster (Parker 1951). In some cases, frequency data are supplemented by recording the nearest perennial plant if a plant does not occur in the ¾-inch plot (Parker 1954). These data are used to determine plant community composition.

Frequency is a nonabsolute measurement influenced by plant density, dispersion, shape, size, and size class distribution (Greig-Smith 1964, Hutchings and Holmgren 1959, Sharp 1954, Smith 1962). Any combination of these factors may affect frequency. Greig-Smith (1964) described frequency as "an uncertain assessment of several different characteristics." It is not possible, with reliability, to relate frequency mathematically to other single plant community characteristics such as basal cover, foliar cover, herbage production, or density (Francis et al. 1972). While frequency may be hard to relate mathematically to other attributes which reflect trend, it still has value when subjectively related to visible changes in photographed characteristics such as cover or density.

The range examiner should know the significance of change in frequency. Biologically, change in plant frequency means live members of a species have, over time, increased or decreased relative to their original presence. This change may have been caused by change in any one or a combination of other plant attributes. In addition, the occurrence of a plant does not necessarily mean that the plant is healthy.

Species recorded as present are often grouped into relative desirability classes for subjective range condition class scorecards. Scorecards, prepared to apply to a particular plant community, assess the current range condition. Changes in scorecard values, over time, imply trend in condition. But because scorecards presently in use depend heavily on frequency and subjective judgments, they cannot be confidently relied upon to indicate trend in condition. Also, condition scorecards have yet to be prepared for some plant communities. For others, scorecards may in some way be deficient because of lack of required ecological understanding.

There is a way, however, to determine more than changes in frequency or scorecard values from 3-step data. It involves identification and interpretation of photographed changes in other characteristics of the plant community. The photographs are thus a valuable part of the method when used to subjectively relate any visible plant community changes to frequency and scorecard changes. This procedure, details of which follow, brings into use all good features of the 3-step method — both subjective judgments and objective measurements.

Framework for Interpretation

A 5-phase procedure has been developed to interpret range trend from 3-step data. Phases 1 and 2 include the standard 3-step procedure for collecting data and tentatively interpreting trend in range condition in the field at the time of measurement. Phases 3 and 4 concern office statistical and photointerpretive procedures, which are then related to the tentative field interpretation. Phase 5 is assignment of cause of trend in condition.

Phase 1

The 3-step procedure should be executed exactly as prescribed, including improvements that enhance the basic method. The best phenological time for species identification and transect reading should be set with strict limits. Past data that do not meet these or other important standards usually should not be used.

Employ any devices that will increase the chance of correct measurement and interpretation. For example, cluster herbariums may be useful where species identification is difficult. Condition scorecards will have the most value if they are refined so they apply to community types within broad vegetation types. High quality photographs are vital for future interpretation. Color photos are preferable.

Phase 2

Next, make a tentative on-the-ground interpretation of short- and long-term trend and its cause. Short-term trend compares the current measurement to the previous measurement, while long-term trend compares the current measurement to all earlier measurements. If available, use valid subjective trend tables based on change in condition scores (Wood and Woolfolk 1960). Carefully compare the past photos to the scene at the time the current transect photos are taken. Any visible and describable evidence of change should be

documented for final office interpretation. Look for changes in basal cover, shrub crown cover, density, plant dispersion, and other factors which may explain changes in frequency.

An on-the-ground judgment of whether short- and long-term trends are up, down, or static should be made primarily for general categories. Such categories as bare soil, total plant cover, forage plant cover, litter, and other characteristics are the most likely to be visible in the photographs. Any other important observable attributes such as density and dispersion should also be noted. Secondarily, trend direction should be judged for one or more important species, especially if they can be identified on the past photos.

While on the cluster area, study both written and visible supplemental information for clues to the cause of trend in condition and document them. Include livestock manipulation, cultural improvements, weather influences, plant diseases, influence of insects, wildlife use, and drastic impacts such as fire.

Phase 3

Gather all data and photos together in the office. Make statistical tests to determine if frequency has changed significantly for plant groups, important species, and nonplant factors. These tests can be made easily on a preprogramed desk calculator or on a computer. Relate statistical tests of frequency to visible photo changes.

Statistical tests for significant trends in frequency require that clusters have two or more transects and three or more years of measurement to meet the minimum requirement for degrees of freedom. Each transect is one sample unit. Therefore, at least two transects are required to get a measure of variance. Vegetation and soil condition scores are summarized for each transect and combined to obtain one condition score for each cluster. Therefore, statistical tests cannot be made for change in condition scores. One-transect clusters and clusters measured only twice are still useful for subjective interpretation. Except for statistical tests, they can be interpreted by most of this procedure, including photos.

For those clusters tested for trends in frequency of plant and soil factors, these tests are useful:

1. Analysis of variance (Cochran and Cox 1957) with orthogonal comparisons to find if:
   a. Differences in frequency between years of measurement are significant. This may indicate a short- or long-term trend.
   b. With repeated measurement over time, some equation best fits changing frequency data (linear, quadratic, cubic, quartic, and so forth). This can indicate the nature of the long-term trend, such as continuous increase, decrease, or a cyclic situation.
   c. Differences in frequency between transects in any one year are significant. This may indicate site confounding within the cluster.
2. Duncan's multiple range test to determine which years of frequency are different from or the same as other years (Duncan 1955). This test sorts years into homogeneous sets of frequency values. It indicates time intervals when short-term trends occurred, or intervals of no change.

Carefully interpret photos, simultaneously viewing photos from all transects and dates. Relate visible changes in important trend indicators (such as basal cover for plant and soil surface factors) to the changes in frequency. Photographic evidence of change, or lack of change, in cover may or may not be supported by results from frequency tests. These possibilities exist:

1. If the photographic evidence of change in some important item, such as cover, is convincing, it should be accepted. If change in cover is in the same direction as significant change in frequency, the two support each other, and change in cover is likely a factor affecting frequency. This is strong evidence of trend in condition.
2. If frequency change is not significant (static), and pictorial evidence of change in some factor, such as cover, is strong a conflict exists. Photointerpretation is accepted, and it is concluded that, while cover has changed, it has not significantly affected frequency. This is mild-to-strong evidence of trend.
3. If convincing photo evidence of change in cover is in opposition with significant change in frequency, a more serious conflict exists. Often it is best to accept changes visible on the photos. For example, when a plant is hit, litter and other soil surface factors are not recorded. Thus, litter and other soil surface factors may appear to be decreasing in frequency while actually increasing in cover. Thus, the photointerpretation may still be mild-to-strong evidence of trend.
4. A situation may exist where photos give no convincing evidence of change in any important attribute. Then more reliance must be placed on the frequency test. This is weaker evidence of trend.

Phase 4

The supportive and nonsupportive relationships between statistical tests of frequency and photographed indicators of trend should be assembled in an orderly way for final interpretation. Keep the management objectives in mind for the particular cluster and site for which it is a benchmark. Relate all the office interpretations (phase 3) to the tentative interpretation of trends made in the field (phase 2). Office interpretations may or may not support tentative field interpretations. Use the strongest of the assembled evidence, and decide direction of trend for both vegetation and soil.

Phase 5

After study of supplemental information, prepare a statement of what agent is interpreted to have caused the trend in range condition. For example, it may be a grazing system or a reduction in livestock numbers and utilization. Other impacts (weather, fire, rodents, game conflicts, range management practices) may be the main causal agent of change, rather than livestock manipulations. If supplemental information is insufficient, it may be impossible to name a cause. For example, weather influences are often different between and during sampling years. The type of growing season should be documented for each measurement year, as well as intervening years, so that weather influences can be considered in the interpretation process. If vital supplemental information is lacking, it should be indicated for collection in the future.

After cause of trend on the cluster area is assigned, range management decisions must be made relevant to current management objectives. These decisions may require allotment inspection on important sites similar to the cluster site. Wise and prompt action is important if range trends are down and condition is less than good.

Examples of 3-Step Condition Trend Interpretation

Two examples follow which illustrate many trend interpretation problems. They illustrate a way to proceed through phases 3, 4, and 5. In these cases, National Forest range examiners made measurements, including frequency, took the photos, and made tentative field determination of trend in range condition (phases 1 and 2). The ¾-inch loop-frequency data will be discussed as frequency, recognizing that different Forest Service Regions use different terminology for this measurement, especially for the larger categories of plant and soil surface characteristics. For example, two Regions retain the original terminology, "plant density index" (Parker 1951), for all the plants recorded on a cluster. Two Regions, including Intermountain Region (Region 4), refer to this as "plant cover index," one Region calls it "total plant hits," and another "plant index." A more precise term would be "total plant frequency." The important point is for a range examiner to know that these various terms refer to the same measurement — frequency. In the examples that follow, Region 4 terms will be retained but discussed as change in frequency.

Soda Springs Cluster

The first example, Soda Springs Cluster, is a three-transect cluster measured four times — 1954, 1959, 1964, and 1969. It is representative of a meadow type on the Caribou National Forest, Idaho.

This cluster is in a slender wheatgrass (*Agropyron trachycaulum* (Link) Malte)-mountain brome (*Bromus marginatus* Ness) plant community. Fifteen other grass and forb species were listed in 1964. The elevation is 7,200 feet, the slope less than 5 percent. Sixty percent of the approximately 25 inches of precipitation comes as snow. The soil is over 3 feet deep with few surface rocks. The site produces an estimated 1,500 pounds of air-dry herbage. Average range readiness date is July 1. Sheep graze the allotment with light deer and elk use. There is pocket gopher activity on the cluster, but of unknown severity.

Phase 3. — Four examples of nine items statistically tested are given (table 1) and related to photographs (fig. 1). Transect 2 photographs shown for four dates illustrate changes representative of those visible on the other two transects. Glossy prints used by the range examiners are of somewhat better quality than the reproductions here.

Plant cover index (frequency) was statistically tested and interpreted on photos (table 1). The increase in mean frequency (7.7 to 28.3) is significant ($P = 0.10$) by the analysis of variance. By orthogonal comparisons, it significantly ($P = 0.05$) fits an upward linear trend.

The multiple range test indicates two homogeneous subsets of mean reading times — 3, 4, and 1, 2, 3. This indicates higher frequency in 1969 (4) than in 1954 (1) and 1959 (2). The

Table 1.--Statistical tests of frequency changes related to photointerpretation of change in other attributes, Soda Springs Cluster, Caribou National Forest, Idaho

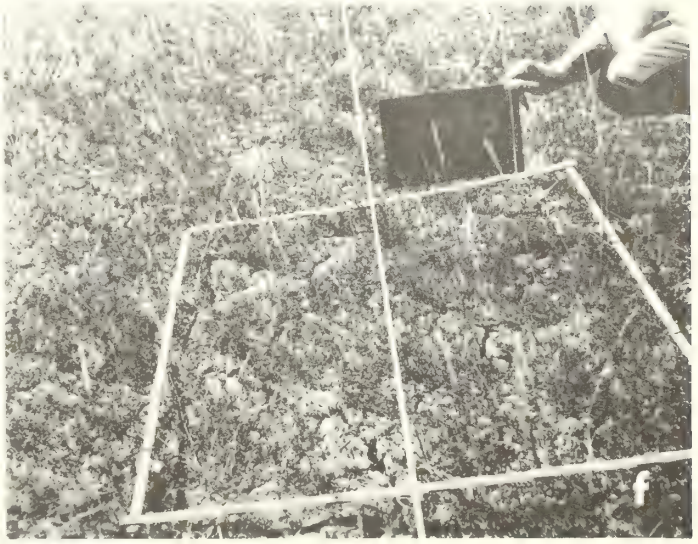
Statistical tests and photo-interpretation	PLANT COVER INDEX					LITTER					BARE SOIL					SLENDER WHEATGRASS				
	(1) 1954	(2) 1959	(3) 1964	(4) 1969	Total	(1) 1954	(2) 1959	(3) 1964	(4) 1969	Total	(1) 1954	(2) 1959	(3) 1964	(4) 1969	Total	(1) 1954	(2) 1959	(3) 1964	(4) 1969	Total
FREQUENCY BY READING TIMES:																				
Transect 1	18	24	11	33	86	26	15	36	39	116	55	60	5[illegible]	25	195	8	7	[illegible]	8	[illegible]
Transect 2	3	3	20	28	54	22	3	39	26	90	73	92	38	44	247	1	1	5	7	14
Transect 3	2	4	19	24	49	34	16	44	51	145	64	80	37	25	206	0	3	3	[illegible]	[illegible]
Year total	23	31	50	85	189	82	34	119	116	351	192	232	127	97	648	9	11	16	14	44
Year mean	7.7	10.3	16.7	28.3	63.0	27.3	11.3	39.7	38.7	117.0	64.0	77.3	42.3	32.3	216.0	3.0	3.7	3.3	4.7	14.7
ANALYSIS OF VARIANCE WITH ORTHOGONAL COMPARISONS:																				
Variation source--	DF	F	Tabular F			F	Tabular F				F	Tabular F				F	Tabular F			
Readings	3	4.63*	3.29 (.10)			21.42**	4.75 (.05)				11.39**	4.76 (.05)				.19 NS	3.29 (.10)			
Linear	1	12.77**	5.99 (.05)			23.92**	5.99 (.05)				23.10**	5.99 (.05)				.39 NS	3.78 (.10)			
Quadratic	1	1.11 NS	3.78 (.10)			6.93**	5.99 (.05)				3.72 NS	3.78 (.10)				.04 NS	3.78 (.10)			
Cubic	1	.01 NS	3.78 (.10)			33.41	5.99 (.05)				7.35**	5.99 (.05)				.13 NS	3.78 (.10)			
Transects	2	1.84 NS	3.46 (.10)			7.77**	5.14 (.05)				1.71 NS	3.46 (.10)				1.50 NS	3.46 (.10)			
Error	6																			
Total	11																			
MULTIPLE RANGE TEST	2 homogeneous subsets of reading times 3, 4 1, 2, 3					3 homogeneous subsets of reading times 4, 3 1 2					2 homogeneous subsets of reading times 1, 2 4, 3					1 homogeneous subset of reading times 1, 2, 3, 4				
PHOTO-INTERPRETATION	Up* Static Down Not clear There appears to be more plant basal cover and higher plant density.					Up* Static Down Not clear More litter covers the soil in both 1964 and 1969.					Up Static Down* Not clear Both soil area is less apparent.					Up Static Down Not clear* Unable to identify individual species on photos. However, perennial grasses appear to have increased in cover, density, and percentage composition.				

examiner can be reasonably certain that frequency has increased, but he does not know why until after studying photos from all three transects for four dates. Through photo-interpretation, he can see that increased plant basal cover and density explains much of the increase in frequency.

Litter is tested in the same way, and is significant (table 1). The test for differences between transects is also significant. Differences are caused by the variation of readings within years. Significance between transects may indicate transects are located on different sites. A ground check should be made if site confounding is suspected. Transect differences could also be caused by examiners' judgment of whether a loop contains more litter or soil.

Frequency trend for litter fits the linear, cubic, and quadratic curves (fig. 2). The cubic curve provides information from all four data points, and is of more value than the other curves. It shows a significant long-term upward trend in litter from 1954 to 1964 and 1969. The cubic also indicates a recent (1964 to 1969) tendency toward a static trend. Assuming management is not changed, this suggests that when the next measurement is made, litter will be relatively unchanged. The multiple range test indicates higher frequency values the last 2 years. This frequency increase in litter is explained in part by a visible increase in litter cover (fig. 1).

Ground cover index sums all frequency values except bare soil. In this case, it is almost entirely the summation of plant cover index and litter, both of which showed an upward trend supported by photointerpretation. For this reason, the analysis is not shown. Because more soil is covered, as seen in the photos, the



August 13, 1954

August 31, 1964

August 21, 1959

September 11, 1969

Figure 1.--Transect 2, Soda Springs Cluster, Caribou National Forest, Idaho.

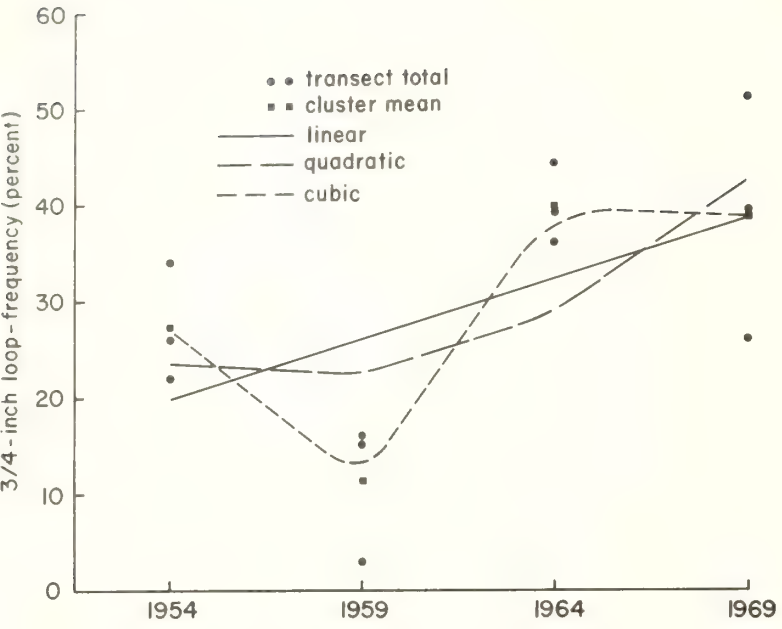


Figure 2.--Significant trend in litter, by years, Soda Springs Cluster (see table 1).

conclusion is that a desirable trend has occurred. Soil erosion hazard is less, and soil stability is probably greater.

Table 1 illustrates a desirable trend of significantly less bare soil. Areas of bare soil are less apparent in the 1964 and 1969 photographs (fig. 1e, h). Therefore, the soil erosion hazard again appears to be less in 1964 and 1969 than in earlier years. The significant cubic test suggests that the rate of increase in soil coverage has slowed since 1964.

The tests for slender wheatgrass (table 1) show no significant change in frequency. This species is not clear on the photographs, which points up the difficulty of detecting change on the photos for sparse individual species. If the two most abundant perennial grasses, slender wheatgrass and mountain brome, are combined, however, frequency increased significantly from 3.3 (1954) to 19.3 (1969). This is supported by a visible increase in cover and density of grasses (fig. 1g, h). The change is an improvement in species composition — an indicator of an upward trend in range condition.

Phase 4. — Consider all the decisions arrived at through tests of frequency related to photointerpretation of change in other attributes. Then decide whether to agree with tentative trend in condition arrived at in the field. Tentative and final trends are shown in the top half of table 2, and results of long-term photo-interpretation are shown at the bottom. Six important factors (bottom, table 2) have changed in frequency, cover, or other factors in a direction that can only be considered a long-term upward trend in both vegetation and soil over the 15-year period. There is a short-term indication, however, that the upward trend in vegetation and soil condition has slowed since 1964. Thus, the interpreter would agree with the tentative trends in vegetation and soil made in the field in 1969.

Other measured or observed items may further support these conclusions. On this cluster there were three supporting items:

1. Current soil erosion — 1954 (severe), 1959 (advanced), 1964 (slight), and 1969 (slight).
2. Plant species composition (ratio of percentages) of desirables to intermediates — 1954 (26/49), 1959 (36/36), 1964 (25/38), and 1969 (42/41).
3. Vigor (height) of slender wheatgrass, expressed as percent of a height standard from a protected area: 1954 (41), 1959 (70), 1964 (81), and 1969 (60). In 1964, this meadow was ungrazed.

Phase 5. — Determine the cause of the trends. Available supplemental information revealed the following facts:

1. Length of summer grazing season for sheep has been constant.
2. Heavy use was common prior to 1954. Since then, grazing has been moderate, except in 1964 when the allotment was ungrazed.
3. Stocking rate was stable prior to 1954. Sheep numbers were reduced substantially in 1954 and 1963.

Table 2.--Trends in range condition related to trends in frequency and photointerpretation of trends in other attributes, Soda Springs Cluster, Caribou National Forest, Idaho

	TRENDS IN VEGETATION				TRENDS IN SOIL			
	TENTATIVE (PHASE 2)		FINAL (PHASE 4)		TENTATIVE (PHASE 2)		FINAL (PHASE 4)	
Year	Short-term	Long-term	Short-term	Long-term	Short-term	Long-term	Short-term	Long-term
1954	static	--			down	--		
1959	up	up			up	up		
1964	up	up			up	up		
1969	static	up	Yes, static since 1964	Yes, up since 1954	static	up	Yes, static since 1964	Yes, up since 1954

RESULTS OF STATISTICAL TESTS OF LONG-TERM CHANGE IN FREQUENCY	PHOTOINTERPRETATION AGREEMENT WITH LONG-TERM CHANGE IN FREQUENCY WHEN RELATED TO OTHER ATTRIBUTES
UP	
STATIC	
DOWN	
Plant cover index	Yes, basal cover up
Forage cover index	Yes, basal cover up
Litter	Yes, more soil covered by litter in both 1964 and 1969
Ground cover index	Yes, more soil covered by plants and litter
Perennial grasses	Yes, basal cover and density up
Soil	Yes, less area of bare soil apparent
Slender wheatgrass	Not clear, species cannot be identified on photos

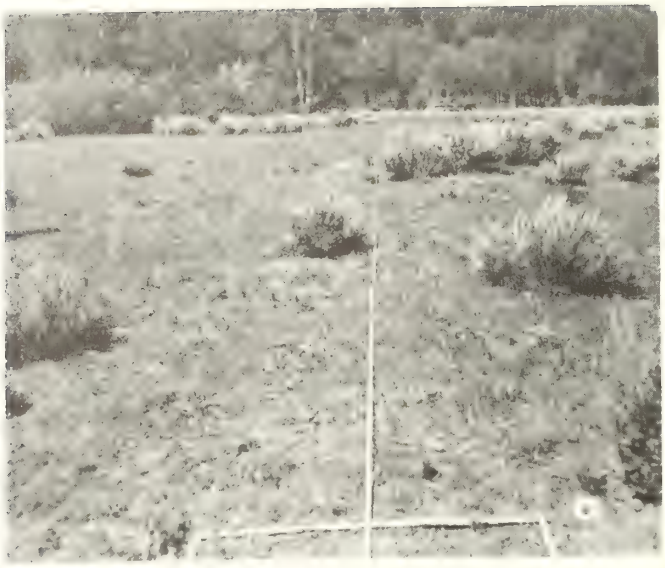
4. Deferred rotation grazing was started in 1954.
5. Big-game use has generally been light and without conflict with sheep.
6. Some destructive pocket gopher activity; no control measures mentioned.

A causal statement can be made as follows: The upward trend in vegetation and soil condition has been the result of introduction of deferred rotation grazing (1954), plus reduction in sheep numbers (1954 and 1963), with consequent lighter livestock use.

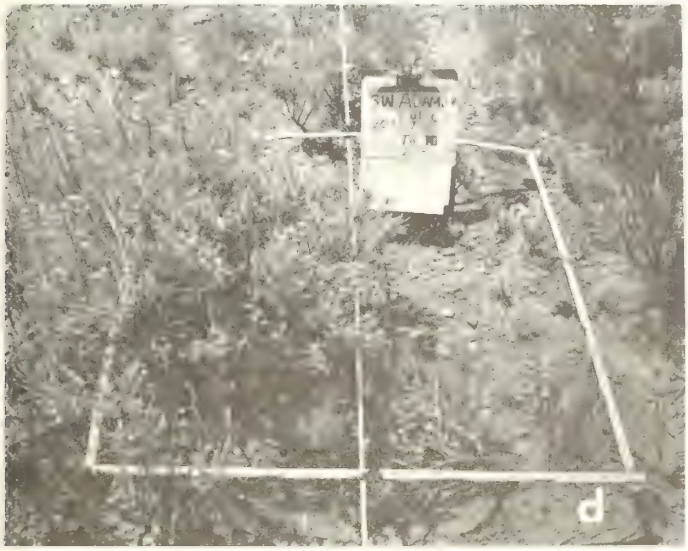
Adams Gulch Cluster

The second cluster example, also in Idaho, is on the Sawtooth National Forest. It is on a relatively flat area within an extensive sagebrush-grass site at an elevation of 6,000 feet. Precipitation is about 25 inches per year, with 60 percent as snow. The soil is a sandy clay loam 2 to 3 feet deep with few surface rocks. The cluster is located within a 60-acre area that was seeded to smooth brome *(Bromus inermis* Layss.) and crested wheatgrass *(Agropyron desertorum* (Fisch.) Schult.) in 1947 to increase the forage supply for cattle. Fourteen other plant species were noted on the area, the most important being big sagebrush *(Artemisia tridentata* Nutt.). Transect 3 illustrates the changes that have taken place (fig. 3), and is representative of what can be seen on the other two transects.

This cluster introduces special problems because of the shrubby layer of vegetation. When the ¾-inch loop hits a shrub crown, the crown is recorded as overstory and a second record is made of the basal frequency beneath the crown. If these basal understory hits are ignored, misleading interpretations of what is taking place at ground level will result. To make the most use of the data, the crown and understory basal hits must be considered separately. Shrub crowns protect the soil from rain, wind, and livestock trampling, but they also have the disadvantage of making the grasses underneath unavailable to livestock. In table 3, the frequency data are presented as they are often summarized — disregarding understory hits. These understory hits are considered, however, in the photointerpretation portion of the table. Even more complex problems can be introduced, over time, by changes in tree canopy which



June 23, 1952



July 25, 1957

July 13, 1962

Figure 3.--Transect 3, Adams Gulch Cluster, Sawtooth National Forest, Idaho.

Table 3.--Statistical tests of frequency changes related to photointerpretation of change in other attributes, Adams Gulch Cluster, Sawtooth National Forest, Idaho

Statistical tests and photo-interpretation	PLANT COVER INDEX				LITTER				BARE SOIL				SMOOTH BROME AND CRESTED WHEATGRASS				BIG SAGEBRUSH			
	(1) 1952	(2) 1957	(3) 1962	Total	(1) 1952	(2) 1957	(3) 1962	Total	(1) 1952	(2) 1957	(3) 1962	Total	(1) 1952	(2) 1957	(3) 1962	Total	(1) 1952	(2) 1957	(3) 1962	Total
FREQUENCY BY READING TIMES:																				
Transect 1	10	31	64	105	22	28	4	54	63	35	27	125	4	8	2	14	6	22	62	90
Transect 2	19	41	50	110	39	18	16	73	40	39	34	113	16	14	3	33	3	24	46	73
Transect 3	7	31	64	102	20	24	3	47	66	38	32	136	4	1	2	7	0	28	61	89
Year total	36	103	178	317	81	70	23	174	169	112	93	374	24	23	7	54	9	74	169	252
Year mean	12.0	34.3	59.3	105.7	27.0	23.3	7.7	58.0	56.3	37.3	31.0	124.7	8.0	7.7	2.3	18.0	3.0	24.7	56.3	84.0
ANALYSIS OF VARIANCE WITH ORTHOGONAL COMPARISONS:																				
Variation source--	DF																			
Readings	2	25.44**	6.94 (.05)		5.01*	4.32 (.10)			5.94*	4.32 (.10)			2.00 NS	4.32 (.10)			63.17**	6.94 (.05)		
Linear	1	50.83**	7.71 (.05)		8.88**	7.71 (.05)			10.97*	7.71 (.05)			3.18 NS	4.54 (.10)			124.88**	7.71 (.05)		
Quadratic	1	.05 NS	4.54 (.10)		1.14 NS	4.54 (.10)			.91 NS	4.54 (.10)			.82 NS	4.54 (.10)			1.46 NS	4.54 (.10)		
Transects	2	.08 NS	4.32 (.10)		.96 NS	4.32 (.10)			.50 NS	4.32 (.10)			3.98 NS	4.32 (.10)			.89 NS	4.32 (.10)		
Error	4																			
Total	8																			
MULTIPLE RANGE TEST	No homogeneous subset of reading times Each mean different from the other.				2 homogeneous subsets of reading times 2, 1 3, 2				2 homogeneous subsets of reading times 1, 2 2, 3				1 homogeneous subset of reading times 1, 2, 3				No homogeneous subsets Each mean different from the other.			
PHOTO-INTERPRETATION	Up* Static Down Not clear				Up* Static Down Not clear				Up Static Down* Not clear				Up Static Down* Not clear				Up* Static Down Not clear			
	More basal and shrub crown cover. Basal frequency alone was 9 (1952), 10 (1957), and 8 (1962) or static; however, this trend is not visible on the photos because of sagebrush crowns.				Larger area of soil covered by litter. Deceptive situation here because litter under shrub crowns is not represented in these frequency values. Actually, basal litter hits (exluding crowns) is 29 in 1962--slightly up or at least static.				There is less area of bare soil, especially if shrub crowns are included.				Based on availability they are down in cover and density because of shrub crown increase. But including hits under crowns, frequency in 1962 is 6 (not 2.3) meaning many seeded plants are present but no longer available.				Crown cover increase is very apparent. Shrub density is up and shrub crown size is increasing. Dispersion of shrubs is more widespread.			

influence the herbaceous and shrubby plant layers. Tree overstory should be measured and considered separately.

Phase 3. — Plant cover index (frequency) is up (table 3) when shrub crown hits and basal hits in the interspace between shrubs are added. Analysis of variance is significant between years; orthogonal comparisons show a significant linear up trend in frequency. The multiple range test indicates that frequency for any one year is significantly different from all other years. From the photos, it is obvious that cover is increasing, especially sagebrush crown cover (fig. 3). However, basal plant frequency (excluding shrub crown hits) is static: 9 (1952), 10 (1957), and 8 (1962). Because of the shrubs, this static trend in basal plant frequency is not visible in the photographs, and understory frequency data must be considered.

Litter can be considered two ways. In table 3, frequency of litter in the openings between shrub crowns was analyzed. It gave a deceptive but significant linear down trend in frequency. When frequency of litter under the shrub canopy was added to that between shrub crowns, however, frequency was 29 (1952), 38 (1957), and 29 (1962), a near static trend. After study of the dense shrub stand in the 1962 photos (fig. 3e, f), it can be reasoned that it was difficult for the examiner, looking through the dense shrub crowns, to accurately estimate litter or soil

within a ¾-inch loop. With shrub leaves, bark, and twigs being shed to become litter, it can be interpreted that a larger area of soil was covered by litter in 1962 than in 1952 — a desirable situation for soil stability.

Statistical tests of bare soil show a favorable linear down trend from 1952 to 1962 (table 3), if shrub crown frequency is included. The photographs show less area of bare soil exposed to rain, wind, and livestock trampling (fig. 3e, f).

The trend of the two seeded grass species, smooth brome and crested wheatgrass, is important (table 3). Their response was the same as forage cover index and desirable plant index because they were the main components of those groups. Statistical tests of frequency for the seeded species show no significant trends, even though the values fell from 8 to 2.3, excluding basal understory frequency. When basal frequency under shrub crowns was included, frequency of the seeded species was 8.4 (1952), 8.3 (1957), and 6.7 (1962), a static situation. Based on evidence of frequency seen on the photos (fig. 3), and availability to livestock, the seeded species show a down trend in basal cover, a decrease in density, and a change in dispersion.

Big sagebrush frequency shows a significant linear up trend due to crown hits (table 3). Photointerpretation shows many attributes that affect frequency have changed. Crown cover has increased, shrub density is up, shrub crown size is larger, individual shrubs are more widely dispersed, and shrub size class distribution has changed from a few large plants in 1952 to many small-to-large plants by 1962.

Phase 4. — Consider all the decisions arrived at through tests of frequency related to changes of other important factors visible on the photographs. Then decide whether to agree or disagree with tentative condition trends arrived at in the field. Tentative and final trends in condition are shown at the top of table 4, and

Table 4.--Trends in range condition related to trends in frequency and photointerpretation of trends in other attributes, Adams Gulch Cluster, Sawtooth National Forest, Idaho

	TRENDS IN VEGETATION				TRENDS IN SOIL			
	TENTATIVE (PHASE 2)		FINAL (PHASE 4)		TENTATIVE (PHASE 2)		FINAL (PHASE 4	
Year	Short-term	Long-term	Short-term	Long-term	Short-term	Long-term	Short-term	Long-term
1952	up	--			up	--		
1957	down	down			static	down		
1962	down	down	Yes, down since 1957 (based on seeding)	Yes, down since 1952	static	down	No, up since 1957	No, up since 1952

RESULTS OF STATISTICAL TESTS OF LONG-TERM CHANGE IN FREQUENCY			PHOTOINTERPRETATION AGREEMENT WITH LONG-TERM CHANGE IN FREQUENCY WHEN RELATED TO OTHER ATTRIBUTES
UP	STATIC	DOWN	
Plant cover index			Yes, basal plus crown cover has increased; basal only is static
	Forage cover index		No, down, forage is being covered by shrub crowns
	Desirable plant index		No, down, desirable plants (seeded species) are being covered by shrubs
Ground cover index			Yes, basal plus crown cover has increased
		Soil	Yes, there is less area of bare soil, especially when shrub crowns are included
		Litter	No, up, if crown hits are excluded, and all basal hits included, a larger area of soil is covered
		Smooth brome, Crested wheatgrass	No, down, decrease in cover and density of available seeded species because of shrub-crown coverage
Big sagebrush			Yes, crown cover is much greater, crown sizes are increasing, shrub density is higher, dispersion is greater

long-term trend results of photo and statistical interpretation at the bottom.

Five important factors have changed. Big sagebrush increased in cover as well as frequency — a long-term downward trend based on the goal of seeding for increased grazing capacity. This increase in big sagebrush has been the main reason that both plant cover index and ground cover index have significantly increased. From a soil condition standpoint, this can be considered a long-term up trend. Litter, while shown as down in frequency as summarized, is actually up or static, if litter under shrub crowns is considered. The trend in litter cover and consequent improved soil protection is an up trend in soil condition, and not a static situation as was judged in the field in 1962.

The two seeded species show no change in frequency, but photointerpretation of shrub understory frequency indicates that herbaceous forage is becoming less available due to increases in sagebrush cover. From the cultural improvement standpoint (seeding for increased livestock forage), this is a vegetation down trend. The 1962 decision also was that both short- and long-term vegetation condition trends were down. Thus, the interpreter would agree with the tentative trends in vegetation judged in 1962, but disagree with the tentative trends in soil.

One other factor supports the long-term down trend in vegetation condition. Species composition (ratio of percentages of desirables to intermediates) has deterioriated badly: 1952 (60/11), 1957 (24/10), and 1962 (4/11).

Phase 5. — The cause of trend is assigned after reviewing the following supplemental information:

1. Cattle have always grazed the allotment from June 1 to September 15.
2. Use has always been very heavy on the area where the cluster is located.
3. Grazing has always been seasonlong.
4. Big-game use has been light and without conflict with livestock.
5. No destructive influences have been documented.
6. Sixty acres of range, including the cluster area, was seeded to smooth brome and crested wheatgrass in 1947, 15 years before the 1962 measurement.

A causal statement can be made. The area seeded in 1947 has returned to a stand dominated by big sagebrush. Heavy seasonlong grazing has been the primary factor in suppressing the seeding, and likely accelerated the increase of sagebrush. This site probably was naturally suited to support a plant community dominated by big sagebrush, so that an ecological change back to sagebrush was inevitable.

Conclusions

Trend in range condition can be interpreted from 3-step data by the following 5-phase approach. It is designed to help range examiners search for evidence of significant and biologically important trends in range condition, and identify causal agents.

Phase 1. — Correctly execute the 3-step procedure in the field at the most appropriate season of the year. This requires proper collection and summary of the required data, and procurement of high-quality photographs. It is also important to document supplemental information to aid in later office interpretation.

Phase 2. — While still in the field, tentatively identify on-the-ground condition trend and its cause. If available, use trend tables based on valid subjective scorecards. Remember that the primary measurement portion of the method is ¾-inch loop-frequency — a plant community character that is both simple (presence or absence) and complex (affected by many other plant community factors). High-quality photographs are essential and should be used to detect visible changes in plant community characteristics other than frequency. Use both documented and visible supplemental information to establish tentative cause of trend.

Phase 3. — In the office, make individual statistical tests of frequency for plant groups, important species, and soil surface factors. Then, by careful photointerpretation, relate change in frequency to plant community changes visible in the photos. Search for visible change in factors that may explain change in frequency. Use all photographs for all measurement dates. The trend interpreter usually has seen the cluster area only once — the current measurement date. Thus, an interpreter is required to detect change in plant community characters from data obtained largely by others. Photographs allow the current interpreter to view the scene and get a visual feel for the characteristics previous range examiners measured and described, as a base for evaluating changes that have since occurred.

Phase 4. — Assemble all statistical changes in frequency and photointerpretation

decisions, and compare these to short- and long-term tentative trend decisions made in the field. By carefully relating all statistically tested changes in frequency to other factors visible in the photographs, it is often possible to determine trend in vegetation and soil condition. It is most important to have this job done by an individual with special knowledge of the mechanisms of ecological change, plus a unique ability to explain the interpretation clearly to others.

Phase 5. — Consider supplemental information, and assign cause of trend in condition. For some clusters, the complexity of the change that has occurred may be impossible to explain. If major modifications in livestock management have occurred, they were likely a major causal agent affecting trends. However, other factors such as weather differences between sampling years, plant diseases, fires, insects, other foraging animals, or human factors often have important effects. If these impacts have not been documented, they may be unnoticed by most range examiners. For this reason, thorough supplemental information is needed, especially for the years between measurements.

Knowing the present condition of rangeland is important. Of more value, however, is the knowledge that range condition is tending, for a known reason, to get better, worse, or remain unchanged. Only then can wise management decisions be made to change undesirable trends or perpetuate desirable trends in range condition.

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The 5-phase procedural framework uses 3-step range trend data to identify important trends in vegetation and soil characteristics and assign cause. Fieldwork is executed under strict procedural rules (phase 1), and current condition and tentative trend are determined (phase 2). Office statistical tests of change in frequency of important species groups, species, and soil surface factors are related by photointerpretation to visible changes in other important indicators of range trend (phase 3). All characteristics that indicate change are grouped and related to trends judged in the field (phase 4), and all available supplemental information is considered and most probable cause(s) of trend assigned (phase 5).

KEYWORDS: Range management, indicator plants, groundphotointerpretation, range plant frequency, 3-step method.

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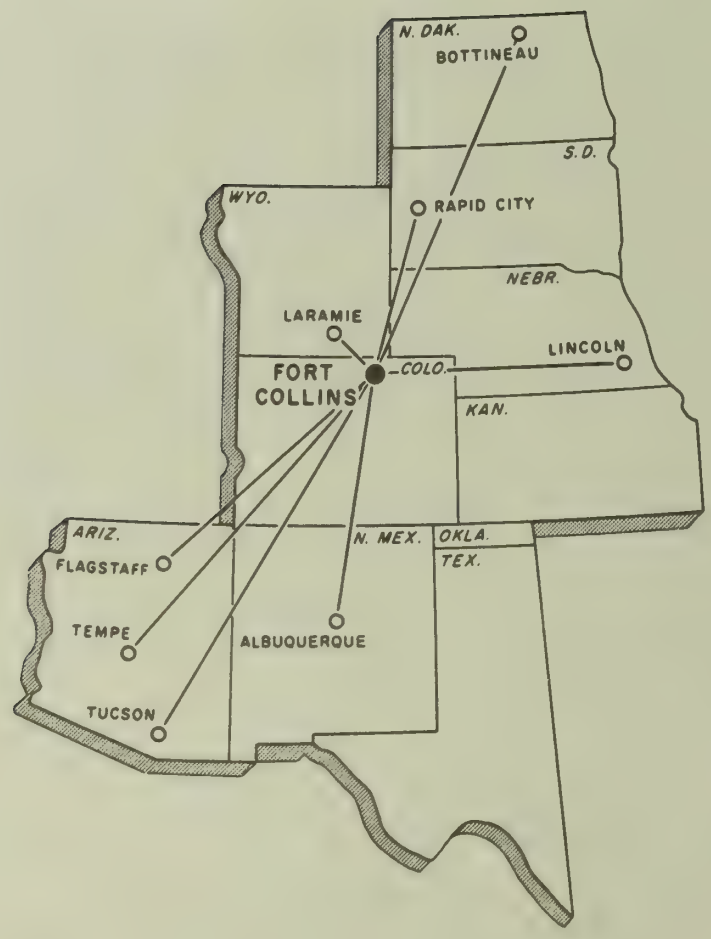
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